THE AIRPLANE AND ITS ENGINE

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PREFACE

Like its predecessors, this edition is intended primarily for the reader who desires a sound knowledge of the basic principles and a broad view of the present development of the airplane and its power plant, without giving to the subject the intensive study which is essential for the designing engineer or the expert mechanic. We have made every effort to introduce nothing which would require more than an elementary knowledge of physics or mathematics for its understanding.

In spite of enormous changes in the aeronautical arts since the edition of 1940, no drastic change in the treatment of basic principles has been found necessary. On the other hand, the stimulus of the Second World War and the resulting developments both during and after the war period have made necessary a complete revision of nearly all the descriptive material. The advent of jet propulsion and the gas turbine has been the most revolutionary of these changes, and due consideration of these developments has been given in this edition, including a separate chapter on jet, turbine, and rocket power plants.

As in previous editions, the basic treatment remains nonmathematical. However, in this edition simple algebraic relations have been added where the text could be strengthened in this way. These additions have made it possible to use the book as a basis for simple illustrative problems. In each case, however, the mathematical portions may be omitted without serious loss to the explanation of basic principles.

The range and complexity of aeronautical equipment as it exists today make it impossible to include adequate descriptions of many items in a brief treatment of this kind. To assist those who wish to supplement the material here presented, the bibliography has been revised and appropriate references have been inserted in the text.

We wish to acknowledge the renewed aid in the shape of data and illustrations which we have received from the National Advisory Committee for Aeronautics, the U.S. Air Forces, the Bureau of Aeronautics of the U.S. Navy, and many manufacturers.

THE AUTHORS

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CHAPTER I

THE ESSENTIAL PARTS OF THE AIRPLANE

The purpose of this chapter is to introduce the terms that are generally used to describe various types of aircraft and their parts. An aircraft is any form of vehicle, generally though not necessarily self-propelled, used for navigation of the air. Its principal use is to transport people or things faster than is possible by surface vehicles.

Aircraft, in general, are divided into two classes—those that are supported by the lifting power of gas, and those that are kept up by motion through the air. Aircraft of the first class are called *lighter than air*, and those of the second class *heavier than air*. The fundamental difference between the two kinds is illustrated by the two familiar toys—the gas-filled balloon, which will rise even in a calm, and the kite, which will fly only in a wind.

The weight of the balloon is supported by the pressure of the air it displaces, whereas the weight of the kite is supported by pressures resulting from the motion of the air past the kite. The kite may also be flown by towing it behind a bicycle or automobile through still air. Motion of the kite relative to the air is the essential requirement.

This book is concerned with but one type of heavier-than-air craft, the *airplane*. This type is supported by rigid wings which do not move with reference to the rest of the machine, is self-propelled, and is ordinarily flown by a human pilot. A fixed-wing aircraft with no means of propulsion is a *glider*. Aircraft with flapping wings are called *ornithopters*, and those with power-driven rotating wings or lifting propellers, *helicopters*. The *autogiro* is also supported by rotating wings, but its wings are rotated in flight only by the motion of the craft itself.

An airplane, like any other vehicle for the carrying of passengers or freight, has four essential parts—a means of support, a means of propulsion, a means of control, and a container for the load that is carried. The airplane is supported by the *wings;* it is propelled by the *power plant;* it is guided by its *control surfaces;* and it carries its load in the *body* or *fuselage*. These essential parts may easily be recognized in a typical airplane.

Flight must be started and finished on land or water. If on the

former, the airplane will be fitted with a *landing gear* and will be called a *landplane*, more often merely an airplane. If on water, the airplane is called a *seaplane*. A seaplane may have *floats* below the fuselage and wings, or the fuselage may form a boatlike hull; in this case the seaplane is called a *flying boat*. Airplanes with both landing gear and hull are amphibians.

The Wings. The wings are light structures with wood or metal framework which extend out on each side of the fuselage. As the airplane moves forward, the air pushes up on the wings and so supports the whole machine. This push or *lift* of the wings is the secret of the support of the airplane.

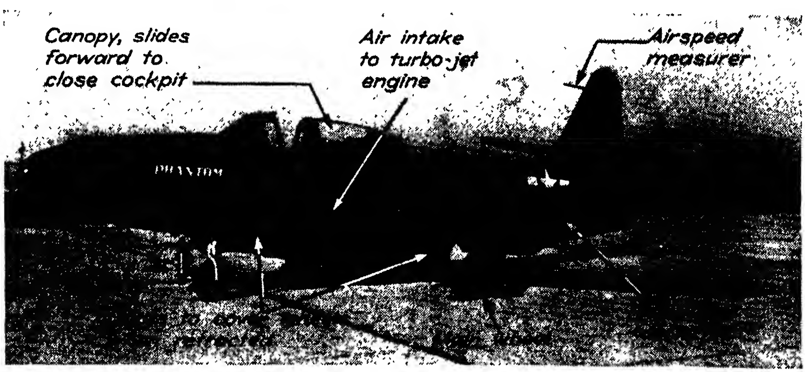


Fig. 1. Low-wing monoplane, Navy twin-jet fighter, FH-1, Phantom. (*McDonnell Aircraft Corporation.*)

The arrangement of the wings determines the names of the different classes of airplanes. If an airplane has only one wing on each side like a bird, it is called a *monoplane*. Such an airplane is shown in Fig. 1. If there are two wings on each side, as shown in Fig. 2, the machine is called a *biplane*. A monoplane is called *parasol, high-wing, mid-wing,* or *low-wing*, from the location of the wing above, or at the top, middle, or bottom of the fuselage. Figure 1 is a low-wing monoplane.

The length of a wing from the tip on one side of the airplane to the tip on the other side is called the *span*, and the distance from the front or *leading edge* of the wing to the rear or *trailing edge* is called the *chord*. If the tip of the wing is higher than the middle, the wing is said to have *dihedral*, and the *dihedral angle* is that between the surface of the wing and the horizontal, as seen from the front. Sweepback is the angle, if any, between the wings and a perpendicular to the longitudinal center line of the airplane, as seen from above. Figure 3 illustrates these and many other terms in airplane nomenclature.

The Power Plant. The next essential part of the airplane is the power plant. Conventional power plants have two principal parts: an internal-combustion *reciprocating engine* roughly like that in an automobile and a *propeller*, roughly an enlarged version of an electric desk fan but with narrow blades. The current of air made by the propeller is directed backwards, thus obtaining the forward force or *thrust* needed to propel the airplane. Usually the propeller is at the front of the airplane mounted directly on the engine shaft. An airplane with this

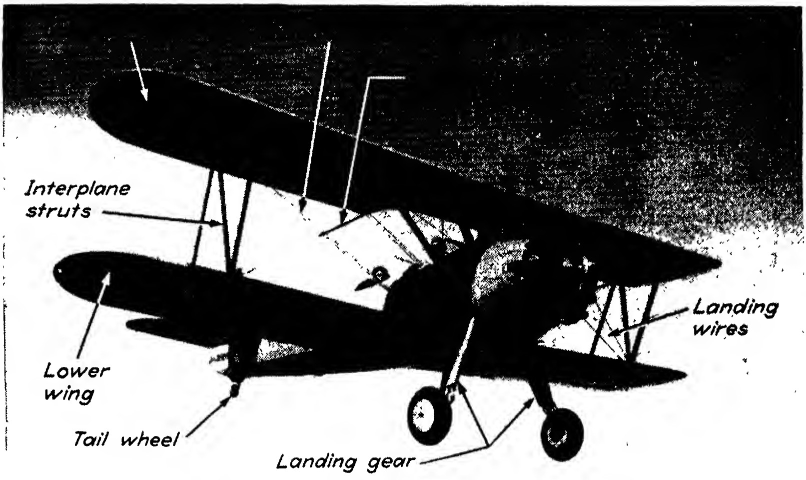


FIG. 2. Biplane, Boeing Trainer, PT-17 Kaydet. Most American pilots in the Second World War first flew this plane. (*Boeing Airplane Company.*)

arrangement is a *tractor*. Occasionally the propeller is at the rear; then the airplane is a *pusher* (Fig. 4).

A radically different power plant is a *turbojet engine.* This has no propeller but instead discharges backward a jet of air and gases at high velocity and temperature, thus creating the forward thrust. The turbojet must be a *pusher.* Air flows into the engine from scoops, is forced by a *compressor* through a *fuel burner* (a much magnified house oil burner). The air and gases at high temperature then expand through nozzles, turn a *turbine* that drives the compressor, and shoot out the tail pipe, thus forming the jet.

A combination of these two types, an *internal-combustion turbine* with a propeller, is called a *turboprop engine.*

In a few experimental types of airplane, the power plant consists of a *rocket engine.* This also has no propeller and obtains its thrust by discharging backward a jet of hot gases at extremely high velocity.

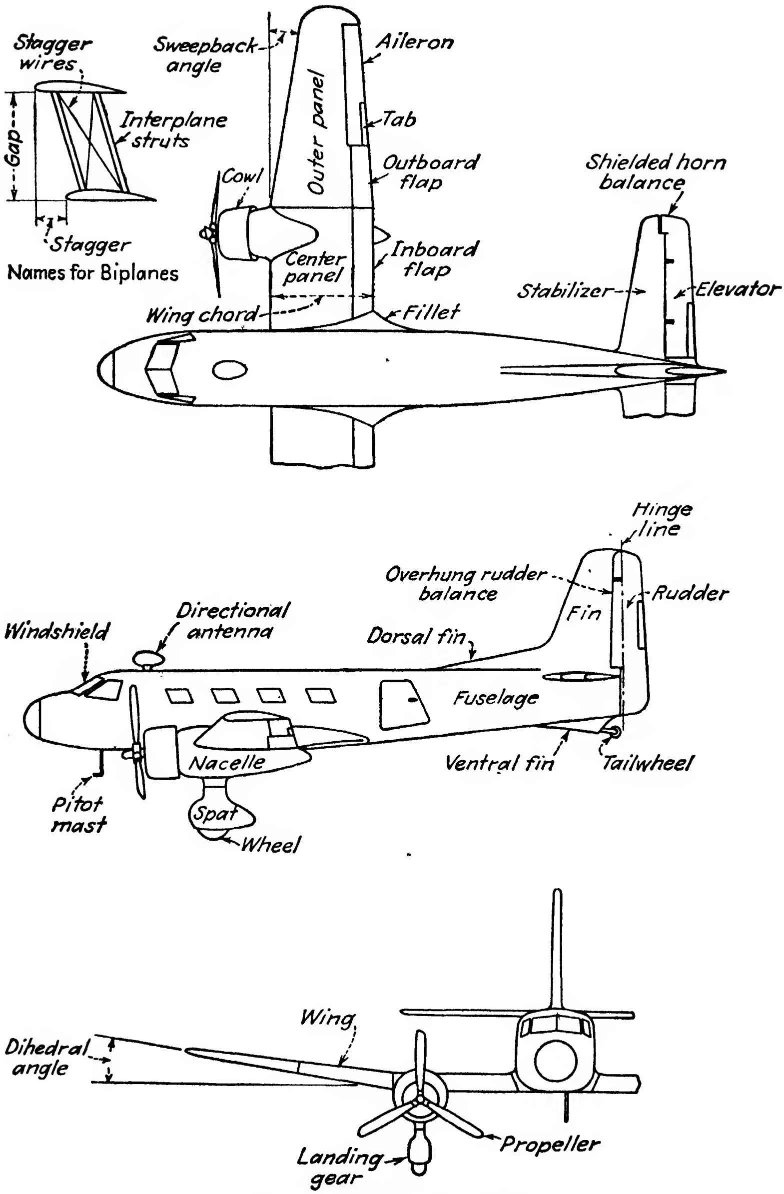


Fig. 3. Airplane nomenclature.

CHAPTER II

AIRFLOW AND THE WING

Before beginning the study of the airplane itself, let us consider the medium in which it moves and by which it is supported. Air is a mixture of gases, of which oxygen forms 21 per cent by volume. The remainder is composed chiefly of nitrogen, though other gases and water vapor are present in small proportions. The oxygen is a vital need not only for the pilot but also for the engine, unless it is a rocket.

Air and Its Motion. Air, like all gases, has neither a definite volume nor a definite shape; it will completely fill any container in which it may be placed; nevertheless, it has mass and weight. The upper layers of the earth's atmosphere, therefore, press down on the lower ones, with a pressure which, small at high altitudes, becomes larger at lower altitudes until at sea level it is 14.7 lb per sq in., or over a ton per square foot. The air pressure acts in all directions, both inside our bodies and outside, so that we are not conscious of it. The size of the pressure is shown by a barometer, which, in simplest form, is a straight vertical glass tube filled with mercury. The tube, sealed at the top, stands in a small dish of mercury. Sea-level pressure pushing on the mercury in the dish forces the mercury 29.92 in. up in the tube, but no higher.

In studying the airplane, we are most interested in the mass of the air. This is small but not insignificant, for a mass of air that occupies a volume of 1 cu ft at sea level weighs on the average 0.0765 lb. The air at sea level is, therefore, said to have a *density d* of 0.0765 lb per cu ft. At higher altitudes, where the pressure is less, the density is also less, and at an altitude of 10,000 ft, for example, it is only 0.0565 lb per cu ft. The average temperature decreases from 59°F at sea level to 67°F below zero at about 35,000 ft above sea level. At about 35,000 ft, the decrease in temperature with altitude ceases, and a constant-temperature layer, the *stratosphere*, commences. At very high altitudes the temperature again increases. Average or *standard atmosphere* relations of interest to airplane designers and operators are given in Fig. 6. Pressures are expressed in inches of mercury, since they are usually determined by a barometer. To convert these pressures to other units:

$$\text{Pounds per square inch} = \text{inches of mercury} \times 0.491 \quad (1)$$
$$\text{Pounds per square foot} = \text{inches of mercury} \times 70.7 \quad (2)$$

Densities are found from the laws of *Boyle* and *Charles:*

$$d = \frac{1.325p}{\theta} \quad (3)$$

where d = density, lb per cu ft
p = pressure, inches of mercury
θ = (temperature, °F + 459.4), called absolute temperature (θ is the Greek letter *theta*, corresponding to t)

Newton's first law of motion tells us that every body will continue to remain at rest, if it is already at rest, or in motion in a straight line, if

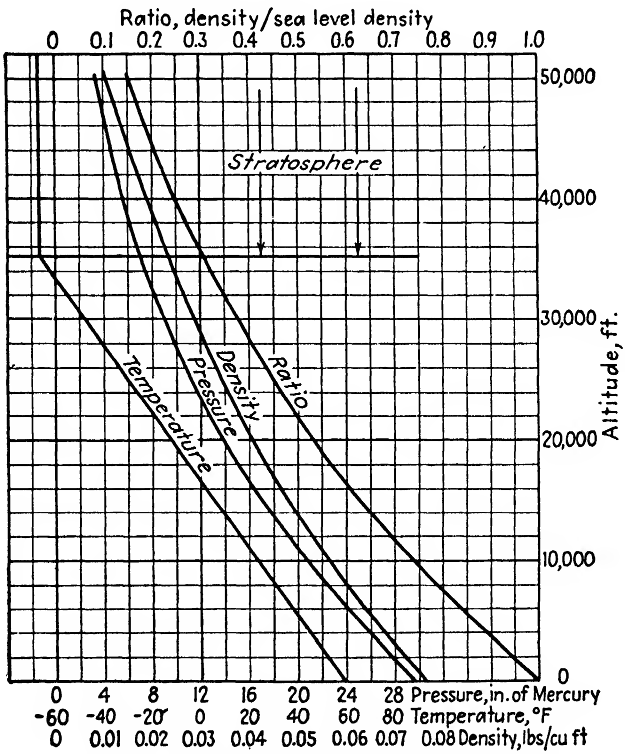


Fig. 6. Characteristics of standard atmosphere.

it is moving, unless some force acts to compel it to change its previous state of rest or motion. Since air has mass, it is a "body" in the meaning of this law. The common palm-leaf fan is a device for setting air in motion, and anyone who has been obliged to use one on a warm

day will readily admit that it takes a very definite force to persuade the air to move. Similarly, one who has tried, perhaps unsuccessfully, to hold an umbrella in a high wind can easily believe that no inconsiderable force is needed to stop or turn aside moving air.

All motion is purely relative; *i.e.*, a body can be said to move only with reference to some other body. For example, if a man sits in his seat in a railway train which is moving forward at a speed of 4 mph, he is moving at 4 mph relative to the ground, but he is not moving at all relative to the car. If, however, he walks toward the rear down the aisle of the car at 4 mph, he is then not moving with respect to the ground, although he has a speed of 4 mph with reference to the train. When the airplane is in the air, the relative motion of the air and the machine is the same whether the airplane moves and the air stands still or the air moves and the machine stands still.

Newton's third law states that to every *action* there is an equal and contrary *reaction*. The function of the wing of an airplane is to deflect downward the air through which it moves. To do this, the wing must push downward on the air, for the air, as we have seen, can be turned aside only by a force. The *action* is then the force which the wing exerts on the air, and the *reaction* is an equal and opposite force with which the air pushes up on the wing. Unless the wing is moving relative to the air, it cannot push the air downward, so there will be no upward reaction or *lift*. It is for this reason that an airplane cannot stay up unless it is moving with reference to the air. In visualizing the motion of the wing through the air, we must always remember, therefore, that the wing is not simply sliding through the air; it is constantly pushing down on it, so that behind the airplane the air is flowing somewhat downward. If the air is not moved downward, the wing cannot create any lift, hence cannot support the airplane.

The Airfoil. In discussing the wing alone, without considering the rest of the airplane, it is customary to speak of the wing as an *airfoil*, which may be defined as a body upon which the motion of the air produces a useful reaction. Unfortunately, the reaction of the air on the airfoil is not entirely a useful force; *i.e.*, it does not act purely to give lift. This force of the air on the airfoil is directed backward as well as upward, for the airfoil, like all other bodies, suffers air *resistance* or *drag*. The wing drag is due partly to the rubbing of air along the surface; this portion is called *profile* or *section drag*.

FIG. 7. Cross section of a typical airfoil.

A typical airfoil is shown in the sketch (Fig. 7). It is not a flat

surface, nor is it an extremely thin one, as it has been found by long experience that some curvature and some thickness are essential if the properties of the airfoil are to be good. The curvature of a line midway between upper and lower surfaces is the *mean camber*, or merely *camber*.

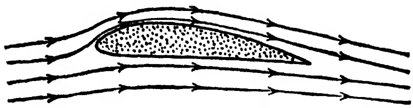


FIG. 8. Streamline flow past an airfoil.

Airflow and Lift. When a moving stream of air encounters an airfoil, part of the air passes above, and part passes below, as shown in Fig. 8. The direction of this flow may be found by experiment on a model airfoil, if smoke is discharged into the air ahead of the airfoil or if very light threads are allowed to trail in the wind. Such a flow, the

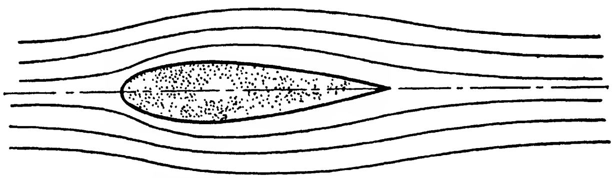


FIG. 9. Streamline flow past a symmetrical body.

stream of air separating smoothly at the leading edge of the airfoil and joining again at the trailing edge without much disturbance, is known as *streamline* flow, and the lines which indicate the direction of the air are called *streamlines*. If the body around which the air is flowing is a symmetrical one, as shown in Fig. 9, and if its axis of symmetry is exactly parallel to the direction of airflow, then the direction of the air

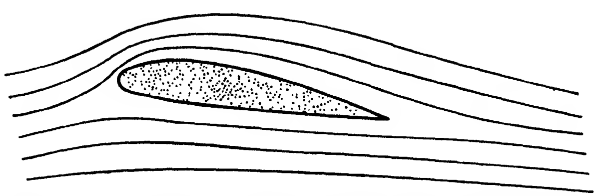


FIG. 10. Flow past an airfoil inclined to the wind direction.

after it leaves the body is the same as it was before it struck the body, and the resulting force on the body acts straight back. If an airfoil is placed in the wind at an angle, as shown in Fig. 10, then the air leaving the wing flows somewhat downward. This downward turning of the wind is known as *downwash*, and because of the downwash the streamlines, as a whole, curve downward. Recalling Newton's first law of

motion, it is apparent that there must be some force acting that compels the air to change its direction and to flow off the airfoil downward instead of straight to the rear. To curve a streamline, force must be continuously acting on the air at right angles to its direction. That such a force is necessary to curve a path may easily be demonstrated by the experiment of whirling a ball on the end of a string. In this experiment, a continuous pull must be maintained on the string if the ball is to travel in a circular path, for as soon as the string is released, the ball flies off straight. The natural tendency of the air to pursue a straight path instead of following a curved one as it passes over the airfoil means that the portion of it on the upper side is constantly pulling away from the wing, while that on the lower side is pushing against it. As a result of this action, the air above the wing is exerting a *suction* on its upper surface, while that below is exerting a *pressure* on the lower surface. The pressure of the air against the upper surface of the airfoil is then less than the normal atmospheric pressure, and that on the lower surface is more. The result of this is that the moving air tends to pull upward on the upper surface and to push up on the lower. There is, in addition, *skin friction* between the air and the airfoil, so that the air pulls backward on both surfaces. The suctions pulling and the pressures pushing also contribute to the back force. The total force is the sum of the effects of these pressures.

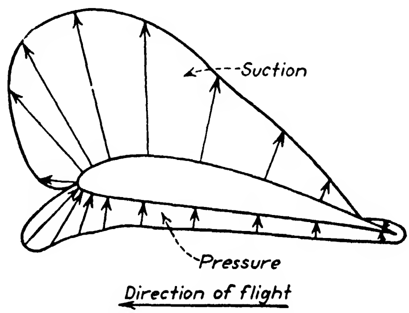


FIG. 11. Distribution of pressure and suction on an airfoil.

The curves made by the streamlines are not arcs of circles, but have varying curvature along their length. More force is required to make the streamlines curve sharply than is required to make them curve gently. This means that neither the suction on the upper surface nor the pressure on the lower is uniform over the area upon which it acts. The curvature of the streamlines is sharpest over the upper leading edge of the airfoil, and it is here that the intensity of suction is greatest. The diagram in Fig. 11 shows the distribution of suction and pressure over the two surfaces of the airfoil. Where the arrows are long, the pressure or suction is great, and where the arrows are short, it is small.

The total suction, or deficiency of pressure, on the upper surface is

considerably more than the total excess pressure on the lower one. For a typical airfoil at a moderate angle of attack, the suction on the upper surface may account for 70 per cent of the total upward force or *lift*, while the pressure on the lower surface contributes only 30 per cent.

Both the intensity and the distribution of pressure and suction vary with the *attitude* of the wing to the moving air. Any particular attitude of the airfoil is designated by the angle of its *chord* to the direction of the relative wind. This angle is called the *angle of attack* and is indicated in Fig. 12. When the angle of attack of the wing is increased from a small value, the curvature of the streamlines becomes sharper, and the angle of downwash increases. The force exerted by the air on the airfoil increases, also. The upper row of diagrams in Fig. 13 shows how the character of the streamline flow over the airfoil changes with the angle of attack, the shaded areas indicating regions of *turbulent flow*. The lower row shows the corresponding changes in pressure intensity and in pressure distribution. It will be noted that, after a certain angle of attack is passed, there is a definite alteration in

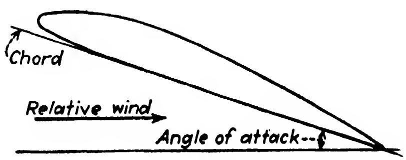


FIG. 12. Angle of attack.

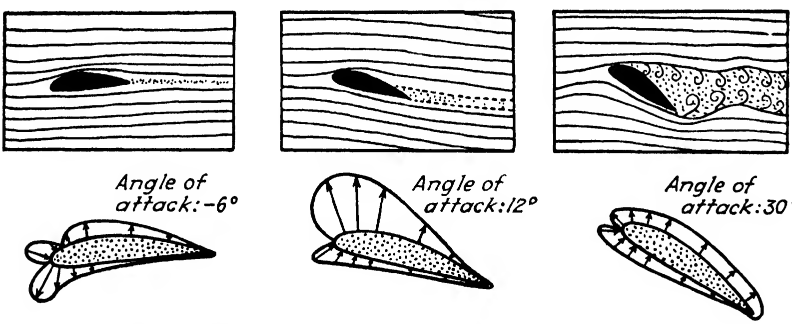


FIG. 13. Change of airflow and pressure with angle of attack.

the character of the flow over the upper surface of the wing. The streamlines break away from the surface, and the air close to the wing becomes turbulent instead of flowing along in smooth streamlines. This region of air is then filled with eddies and vortices, and the flow at any one point varies constantly, both in direction and in velocity. As soon as turbulence appears, the suction "breaks down" to a large extent, for the air pressure in the turbulent region is approximately that of the atmosphere. The total force on the surface is consequently

reduced. The angle of attack at which this phenomenon first appears is known as the *critical angle* or *stalling angle*. The phenomenon is called *stalling*.

Resultant Force and Center of Pressure. The aggregation of small individual pressures acting all over the surface of the wing can be replaced for purposes of discussion and analysis by a single force known as the *resultant*. The magnitude of this resultant is equal to the sum of the magnitudes of all the individual forces, and its direction is the average of the directions of the little forces, with due allowance for the greater importance of the larger individual forces in determining the direction of the resultant.

This replacement of individual forces by an equivalent resultant is analogous to the process of weighing an automobile upon a platform scale. The automobile exerts four individual forces upon the scale, one for each wheel, but the indicator of the scale reads only the resultant of these forces, *i.e.*, their sum, and the effect upon the scale of the four individual forces is exactly the same as that which would be obtained if these four forces were replaced by a single resultant force. In the automobile, we are much more interested in the total weight than in the weight on each individual wheel, and, similarly, for this part of the discussion on airfoils, we are more interested in the total force which acts on the airfoil than we are in the individual forces.

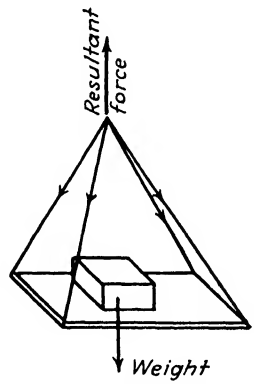


FIG. 14. Location of resultant force.

To represent correctly the complete effect of the individual forces, it is not enough for the resultant to be correct in direction and magnitude; it must also be correct in location. This may be illustrated by employing the analogy of a platform being lifted by ropes at its four corners. Let us assume that these ropes join in a single rope above, as shown in Fig. 14. The resultant of the individual forces in the four ropes is clearly the single force in the main rope, and it is quite apparent that there can be only one location for this resultant force, for, if it is moved in any direction from this location, the platform will immediately tip. In precisely the same way, there is a definite location for the resultant of the forces on the airfoil. The point at which the line of action of this resultant force intersects the chord of the airfoil is known as the *center of pressure*, because it is the point about which all

the individual pressure and suction forces will balance. The center of pressure is indicated in Fig. 15. If a model airfoil is supported in a wind stream on a pivot which passes through this center of pressure, it will then be in equilibrium and will have no tendency either to tip forward or to tip back.

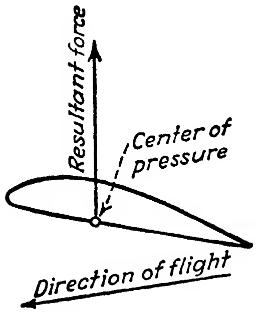


FIG. 15. Center of pressure on airfoil.

Lift and Drag Forces. It is very convenient to replace the single resultant force by two component forces which act at right angles to each other, as shown in Fig. 16. The first of these forces is called the *lift*, and it may be defined as that component of the resultant force which acts in a direction perpendicular to the direction of the relative wind. The other force is called the *drag*, and it acts parallel to the relative wind. The resultant and its two components evidently have the same relation to one another as the hypotenuse and the two sides of a right triangle. Consequently, the square of the magnitude of the resultant force will always be equal to the sum of the squares of the magnitudes of the two components. Thus, if the lift on a certain model airfoil is 6 lb and the drag is 1 lb, the resultant must be 6.08 lb.

If an airplane is flying on a level course, the lift force acts vertically and supports the airplane, and the drag force acts horizontally backward and resists the motion of the airplane through the air. The lift is, therefore, a useful force, and the drag is a useless one that must be accepted in order to get the lift. Since the air offers resistance to any body moving through it, we can under no circumstances obtain a lift force without a corresponding drag. The object of the designer of the airfoil is, therefore, to obtain the most lift with the least drag. Other things being equal, the best airfoil is that which gives the highest ratio of lift to drag, *i.e.*, the highest L/D ratio.

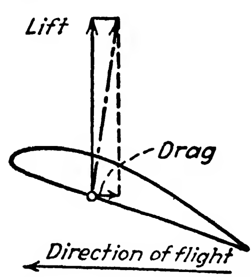


FIG. 16. Lift and drag forces on airfoil.

It should be emphasized that the resultant force, the total lift, and the total drag are concepts in the mind of the aeronautical engineer. The actual forces are the innumerable pressures and suctions distributed over the whole area of the wing; the resultant force and, consequently, the lift and drag components are to be regarded chiefly as

convenient ways of representing this aggregation of very small individual forces. The individual pressure and suction forces may be replaced in the discussion by the equivalent resultant force, and that, in turn, by the equivalent lift and drag forces. Since the individual forces depend on the angle of attack of the airfoil, so also do the resultant or its two components.

Dependence of Lift and Drag upon Angle of Attack. Although there is a very definite relationship between the magnitude of the lift and drag forces and the angle of attack, this relationship cannot be expressed by a mathematical equation. The lift increases when the angle of attack is increased from some small angle up to the *stall*. By properly adjusting the angle of attack, the lift can be made zero, though the angle for zero lift is generally one less than 0°, as shown in Fig. 17. The drag force is never zero, no matter what the angle of attack, and, unlike the lift, does not decrease but increases as the airfoil stalls. The most convenient way of expressing the relationships

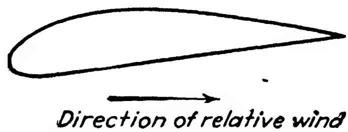


FIG. 17. Airfoil at angle of zero lift.

TABLE 1. RESULTS OF TEST OF MODEL AIRFOIL, 36 BY 6 IN.
Air speed, 40 mph

Angle of attack, deg	Lift, lb	Drag, lb
−6	−0.231	0.115
−4	0.654	0.091
−2	1.550	0.096
0	2.495	0.119
2	3.364	0.168
4	4.263	0.236
6	5.115	0.319
8	5.930	0.412
10	6.635	0.522
12	7.263	0.635
14	7.624	0.779
16	7.217	1.029

of lift and drag to angle of attack is by means of curves or graphs, as in Fig. 18.

Here the values of the angle of attack are shown on the horizontal scale, and the corresponding values of lift and drag are shown on the vertical scales. The information necessary for plotting these curves

is obtained by measuring the forces upon a small model airfoil in a wind stream of known velocity. Ordinarily, two *balances* are used, one to measure the force perpendicular to the wind direction, *i.e.*, the lift, and the other to measure that parallel to the wind, the drag. The airfoil is first set at a small angle of attack, and the lift and drag for this angle are measured and recorded. The angle of attack is next

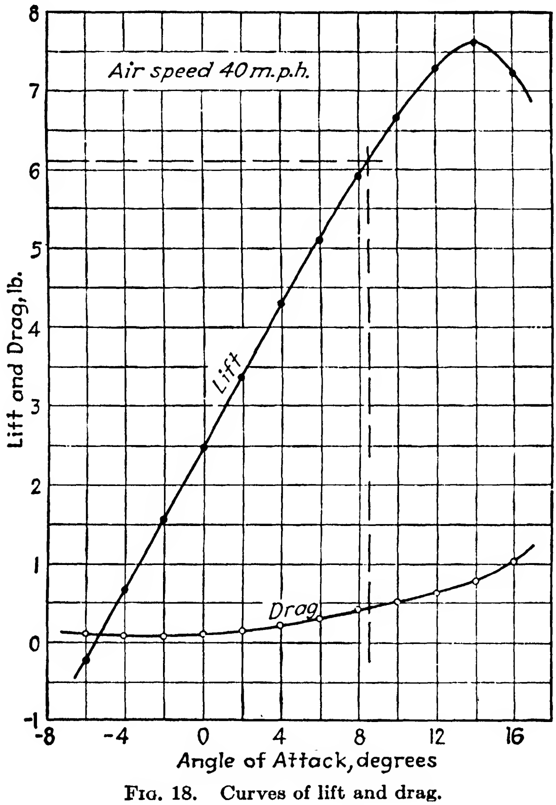


FIG. 18. Curves of lift and drag.

increased and a second pair of values of lift and drag obtained, and the process is continued until the critical angle has been passed. Sample test results are given in Table 1, and curves of lift and drag vs. angle of attack are plotted on Fig. 18.

The manner in which the lift of the airfoil varies with the angle of attack is evident from Fig. 18. The lift is zero at an angle of $-5.4°$. From this point, the lift increases almost uniformly with angle of attack until an angle of 12° is reached. From here the rate of increase is less rapid, and at 14° the maximum value of the lift is attained. This is

the critical, or stalling angle, and beyond it the lift decreases. In airfoils of different shapes the values of the maximum lift may be different, and these maximum values may be reached at different angles, but the lift of every airfoil has a maximum value at some angle of attack.

The drag curve shows that the drag is a minimum when the angle of attack is $-3°$. If the angle of attack is made smaller or larger than this, the drag increases.

Effect of Air Speed and Density on Lift and Drag. The pattern of the streamlines around the airfoil changes with the angle of attack but not with the speed of the relative wind unless that speed is very high, above about 600 mph. The curvature of the flow lines at any point is not affected by the air speed. In physics we learned that the force needed to make an object travel in a curved path of a given radius is proportional to the weight of the object and the square of the speed along the path.

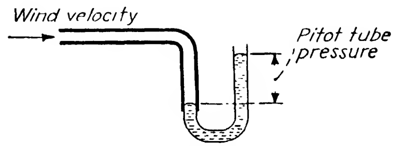


FIG. 19. Pressure given by a pitot tube. Dynamic pressure

$$\underset{\text{lb/sq ft}}{q} = \underset{\text{factor}}{0.0334} \times \underset{\text{lb/cu ft}}{d} \times \underset{\text{mph}}{V^2}$$

This law may be used to find the variation of the pressure on the surface of the airfoil with air speed, if one realizes that the pressure, say, on the bottom, is the sum of the forces at that point needed to curve down all the streamlines below the airfoil and replaces the weight of the object with the unit weight, *i.e.*, the density, of the air. Our new rule is

$$P = kdV^2 \tag{4}$$

where P = pressure, lb per sq ft
d = density, weight of 1 cu ft of air
V = air speed (most conveniently in miles per hour)
k = a number whose value depends on the shape of the airfoil, the angle of attack, and the location on the surface

Near the leading edge the airflow divides, part flowing over the upper surface, the rest over the lower. At the point of division the velocity of flow along the surface must fall to zero; hence the point is called the *stagnation point*. At the stagnation point the largest excess of pressure above normal occurs. The amount, independent of the shape of airfoil or angle of attack, is the same measured by a pitot tube in the air stream (Fig. 19). The pitot-tube or stagnation-point pressure is nearly equal to a pressure called the *dynamic pressure*, except when the air speed is very high. The dynamic pressure, often indicated by the symbol q, is a convenient unit for reference of other pres-

sure. At 100 mph at sea level, q is 25.6 lb per sq ft, while at 500 mph it is 640 lb per sq ft. At the latter speed the stagnation-point pressure is about 10 per cent larger than the dynamic pressure.

From the stagnation point the air flows along the upper surface into a low-pressure region. As this occurs, the velocity along the surface increases, since by the principle of the conservation of energy, as the air loses pressure (potential) energy it must gain kinetic energy (velocity). This relation is expressed formally by *Bernoulli's equation* for flow of any fluid. The action is quite like that of a ball on a smooth hill. The stagnation point corresponds to the hilltop from which the ball may roll in either direction with increasing velocity, gaining kinetic energy as it loses potential energy.

The velocity along the surface will exceed the stream velocity at all points at which the pressure is diminished below the stream pressure. The *pressure coefficient* is defined

$$P_c = \frac{P_{\text{surface}} - P_{\text{atmos}}}{q} \tag{5}$$

and

$$\frac{V_{\text{surface}}}{V_{\text{stream}}} = \sqrt{1 - P_c} \tag{6}$$

if the velocity and P_c are moderate.

The intensity of pressure at any point varies directly as d and V^2. Therefore, since the total force is obtained by adding the forces all over the surface, it too will vary as dV^2. Lift and drag forces are merely components of the resultant force, so each will vary as dV^2. The dynamic pressure q varies as dV^2, so we may say also that the lift and drag vary directly as q.

Effect of Size on Lift and Drag. If the size, but not the shape or the angle of attack, of the airfoil is increased, the flow pattern is enlarged but remains similar to the original, exactly as a photographic enlargement is similar to its original. Therefore, the intensity of pressure at corresponding points on small and large airfoils will be the same at the same dynamic pressure, and the lift and drag forces will be proportional to the areas of the two airfoils. The area of an airfoil or wing is the projected area in the plan view as seen when looking up at a plane flying directly overhead. The usual symbol for area is S (surface).

Lift and Drag Coefficients. The engineer who is designing an airplane is interested in the lift of a model airfoil under test as a means of predicting what the wing of his airplane will lift in flight.

In the last two sections we have learned that, for geometrically similar airfoils at the same angle of attack, L varies as q or dV^2—same size; L varies as S—same q. Combining these,

$$L = C_L S q \tag{7}$$

C_L is called the *lift coefficient.* It depends upon the shape and angle of attack of the airfoil. If its value is determined by an experiment, the lift of any size of airfoil of the shape tested at any speed may be calculated. C_L is the ratio of the average lift per square foot, L/S, to the dynamic pressure q.

Figure 18 shows that the lift at an angle of attack of 8° for this airfoil was 5.93 lb. The chord was 6 in. and the span 36 in.; hence its area S 1.5 sq ft. The wind speed was 40 mph, the air density 0.0765 lb per cu ft. First find q, the dynamic pressure.

$$\begin{aligned} q &= 0.0334 dV^2 \\ &= 0.0334 \times 0.0765 \times 1{,}600 \\ &= 4.09 \text{ lb per sq ft} \end{aligned} \tag{8}$$

Then

$$\begin{aligned} L &= C_L S q \\ 5.93 &= C_L \times 1.5 \times 4.09 \end{aligned}$$

from which $C_L = 0.97$.

If similar calculations are made for other angles of attack, a curve showing the variation of lift coefficient with angle of attack may be plotted, as in Fig. 20. From this curve the lift of a similar airfoil of any size may be calculated for any combination of air speed, air density, and angle of attack. Suppose we wish to know the lift on a wing of 250 sq ft area at 8° angle of attack, at 120 mph with sea-level density, $d = 0.0765$. First find q.

$$q = 0.0334 \times 0.0765 \times 120^2 = 36.9 \tag{9}$$

C_L from curve at 8° is 0.97.

$$\text{Lift} = 0.97 \times 250 \times 36.9 = 8{,}950 \text{ lb} \tag{10}$$

In an analogous manner *drag coefficients* C_D may be calculated from

$$\text{Drag} = C_D S q \tag{11}$$

and plotted against angle of attack. For the sample wing this also has been done on Fig. 20.

Speed and Angle of Attack. While further consideration must be given later to the forces on an airplane in flight, two very important

facts can be learned from studying lift-coefficient curves similar to Fig. 20. An airplane always flies with its wings at an angle of attack equal to or less than the stalling angle of the wing, since control is insufficient above that angle. Therefore (1) any lift coefficient is found at only one angle of attack, and at any angle of attack there is only one lift coefficient; (2) there is a maximum value of the lift coef-

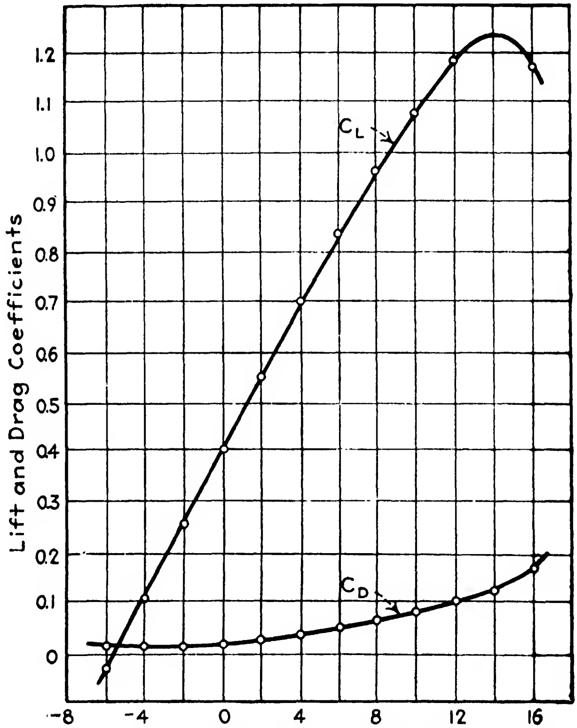


FIG. 20. Curves of lift and drag coefficients.

ficient, the magnitude varying with type and arrangement of the wing; a fair average value for wings of fixed shape and area is 1.4.

The lift on the wings is very nearly that on the entire plane. In steady level flight the lift must just equal the total weight of the airplane W.

$$\text{Lift} = \text{weight}$$
$$L = C_L S q = W \tag{12}$$

Reasoning from this equation, at any value of C_L, an airplane of fixed total weight and wing area can fly at only one value of the dynamic

pressure, and, at constant air density, at only one air speed. Remember, "at any value of C_L" is the same as "at any angle of attack." Conversely, a given airplane can fly at one air density at any desired air speed at only one angle of attack.

$$W = C_L S q$$

Substituting for q its value

$$q = 0.0334 d V^2 \tag{13}$$
$$W = C_L S \times 0.0334 d V^2 \tag{14}$$
$$V = \sqrt{\frac{W}{S}} \frac{1}{\sqrt{0.0334 d C_L}} \quad \text{mph} \tag{15}$$

The fraction W/S is called the *wing loading.* Our equation says that all airplanes with the same wing loading will fly at the same air speed at the same lift coefficient (or angle of attack) and air density. It also says that the product $V\sqrt{d}$ will be constant for all planes of the same wing loading and lift coefficient. Since at altitude the air density d is smaller, the airplane must fly faster in order that the wings may supply a supporting force equal to the weight.

The fact that for any fixed wing arrangement, there is a maximum value of the lift coefficient tells us that there is a certain dynamic pressure below which an airplane of a given wing loading cannot fly, or that at any value of the air density there is a *minimum air speed.* An airplane usually lands at an air speed very nearly equal to its minimum speed. The speed over the ground (or water) will be the air speed less the wind velocity, since pilots, like birds, always alight facing the wind. Just as the angle of attack of maximum lift coefficient is called the *stalling angle,* the minimum air speed is called the *stalling speed.*

Suppose the average value of the maximum lift coefficient is substituted in the lift equation with sea-level density.

$$V_{\min} = \sqrt{\frac{W}{S}} \sqrt{\frac{1}{0.0334 \times 0.0765 \times 1.4}}$$
$$= 17\sqrt{\frac{W}{S}} \tag{16}$$

So the landing speed at sea level is about 17 $\sqrt{\text{wing loading}}$ miles per hour for wings of fixed section. When the wing loading is 6 lb per sq ft, the landing speed is 42 mph; for 9 lb it is 51 mph; for 16 lb, 68 mph, etc. If the wings are fitted with flaps (see Chap. III), the constant in the landing-speed equation will be from 16 down to about 13.

Center of Pressure. It has already been pointed out that the distribution of the individual pressure and suction forces over the airfoil varies with the angle of attack, and it is natural, therefore, that the location of the resultant force should likewise vary with angle of attack. Figure 21 shows the location of the resultant force on an airfoil of usual shape of median line for three different angles of attack. As the angle

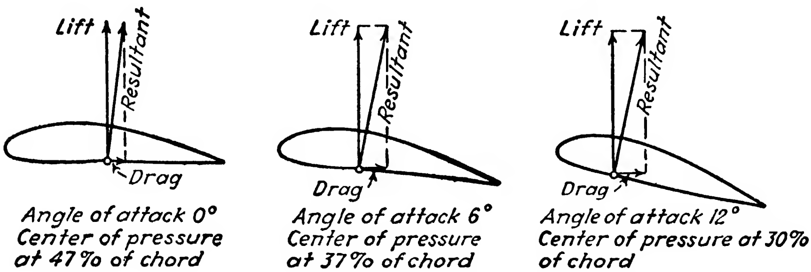


FIG. 21. Movement of center of pressure with changing angle of attack.

of attack increases, the resultant and consequently the center of pressure move forward; if the angle decreases, the center of pressure moves back.

The curvature of the usual median line of an airfoil is always concave downward. The amount of travel of the center of pressure is large if the mean camber is large, small if the camber is small. The center-of-pressure travel may be made zero or reversed in direction by bending the trailing edge of the airfoil up. The median line would be a reverse

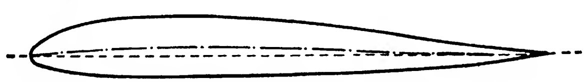


FIG. 22. Airfoil with small center of pressure movement.

curve. Figure 22 shows an airfoil of very small center-of-pressure travel. It is generally desirable that an airfoil used as a wing should have a small center-of-pressure travel.

For most airfoils the product of the lift coefficient and the distance, expressed as a fraction of the chord, from the center of pressure to a point called the *aerodynamic center* is constant. The aerodynamic center is at about 24 per cent chord. The product is the moment coefficient of the airfoil.

$$C_m = \frac{\text{moment}}{Sqc} = C_L \frac{\text{arm}}{c} \tag{17}$$

where moment = force × arm

c = chord, ft

For an airfoil with center of pressure back of the quarter-chord point

(median line always concave downward), the moment is always *diving* or negative.

Effect of High Air Speed. By high air speed, velocity above 500 mph is meant. At low or moderate speeds the flow pattern around a body changes with shape and attitude of the body, but is practically independent of the air speed. Changes in density of the air are small because changes in pressure due to the airflow are small relative to the atmospheric pressure. The dynamic pressure at 100 mph has already been given as 25.6 lb per sq ft. Except at large lift coefficients, the pressure reduction is less than twice the dynamic pressure, or, at 100 mph, 50 lb per sq ft, only 2½ per cent of the total pressure, causing hardly enough change in density to affect the flow pattern. At 500 mph, q is 640 lb per sq ft, and the pressure reduction may be 1,200 lb per sq ft or over half the atmospheric pressure. If it is, the flow pattern will be completely changed. Just back of the minimum-pressure point, abrupt changes in pressure and density occur. These were made visible in the accompanying photograph (Fig. 23) by shining light through the air in such a way that regions in which sudden pressure changes occur appear as dark streaks. These sudden changes in pressure are called *shocks* or *shock waves.* Their presence means some increase in drag and; owing to disturbed flow behind the shock, causes further increase in drag, loss of lift, and an abrupt jump in center of pressure.

A shock formed on a wing disturbs the flow behind the wing. If the tail is within the disturbed area, dangerous loss of control or vibration of the surfaces may occur. Either may be severe enough to cause loss of plane and crew.

At speeds higher than 500 mph shocks are formed even if the pressure reduction is much less than twice q. The shock will form if the minimum pressure is less than half the atmospheric pressure. The air speed at which a shock first forms is called the *critical speed.*

If the local pressure is less than half the atmospheric pressure, the local velocity, by Bernoulli's relation, exceeds that of sound in air (about 750 mph at sea level, falling to 650 mph at high altitudes). Hence, from the previous paragraph, shock waves occur only if the local velocity exceeds that of sound. This is because the velocity of sound is the speed of motion of a small pressure change or impulse through the air. Such an impulse cannot be transmitted upstream if the local velocity is supersonic; hence tiny impulses originating at the trailing edge pile up into a shock at the back end of the supersonic region.

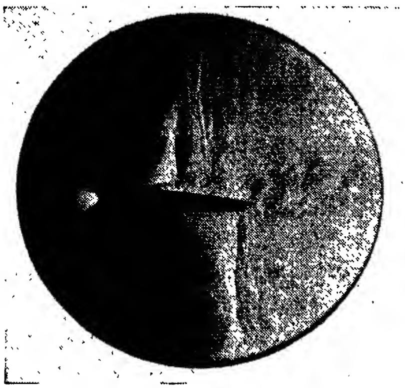


Fig. 23.

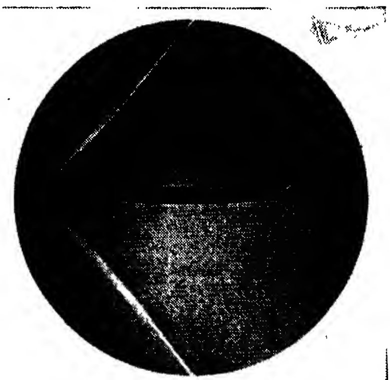


Fig. 24.

Fig. 23. Schlieren photograph of flow at 615 mph past NACA 23015 airfoil, angle of attack 3°. (*NACA photograph.*)
Fig. 24. Schlieren photograph of NACA 6 per cent circular-arc airfoil, angle of attack 0°, Mach number 1.5, air speed 1,140 mph. (*NACA photograph.*)

The ratio of the speed of the airfoil or airplane to the speed of sound is called the *Mach number*. In Fig. 23, the Mach number is 0.82.

Effect of Supersonic Air Speed. If the speed of the airplane is supersonic, *i.e.*, if the Mach number is greater than 1, a third radically

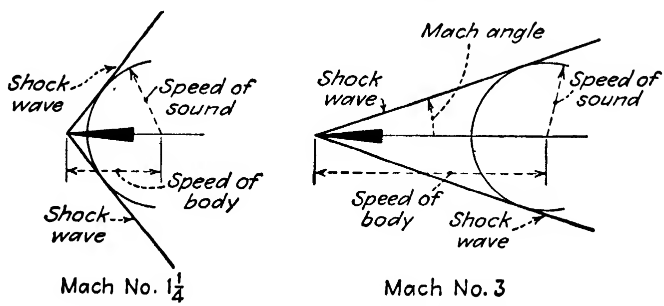


Fig. 25. Angle of shock wave in supersonic flow.

different flow pattern is formed (Fig. 24). As shown, the principal shocks are now formed at the nose. That is because the wing or airplane cannot send advance notice to the air particles to form a smooth flow around the nose. In subsonic flow the air pressure ahead of the body increases gradually until it reaches the stagnation pressure; but in supersonic flow no changes in pressure can be made ahead of the body, which arrives suddenly, forming a shock wave. If the airfoil or other body is sharp-nosed, the shock will be attached to the nose as shown. If, however, the nose is more blunt, a heavy shock will be

formed a short distance in front of it, normal to air stream near the axis, then curving back. The attached shock is nearly straight but makes an angle with the normal to the air stream; hence it is called an *oblique shock*. If the Mach number is only slightly greater than 1, the oblique shock is nearly normal to the wind direction, but at a large Mach number the wave is well back of the normal, and the velocity may be estimated from measurements of the shock angle if the body is thin and sharp-nosed (Fig. 25). A wind tunnel for studying supersonic flow is shown in Fig. 26; the air stream is seen through the porthole on the left.

FIG. 26. NACA supersonic wind tunnel. (*NACA photograph.*)

When shocks are formed at the nose as in flight at supersonic speed, the drag coefficient is increased to several times its value at low Mach number. To minimize this increase in drag, wings and other parts of an aircraft that flies at supersonic speeds must be extremely thin and sharp-nosed. The drag at 1,100 mph of a plane the size and weight of a Mustang, which can fly at about 450 mph, would be roughly eighteen times as much as that of the Mustang and require over 50,000 hp. No available power plant except a rocket engine could develop that power within a fuselage the size of a Mustang's. Hence in the immediate future supersonic airplanes will not be generally used, and, for the present, except for experimental types or special military planes, will be pilotless aircraft rather than piloted airplanes.

In Fig. 27 are shown comparative lift and drag coefficients for a wing at low air speed, at about 500 mph (Mach number 0.65), at about 600 mph (Mach number 0.8), and for another shape at about 1,400 mph (Mach number 1.85). Notice that the earliest effect of the high Mach number and resulting shock waves is to reduce the maximum

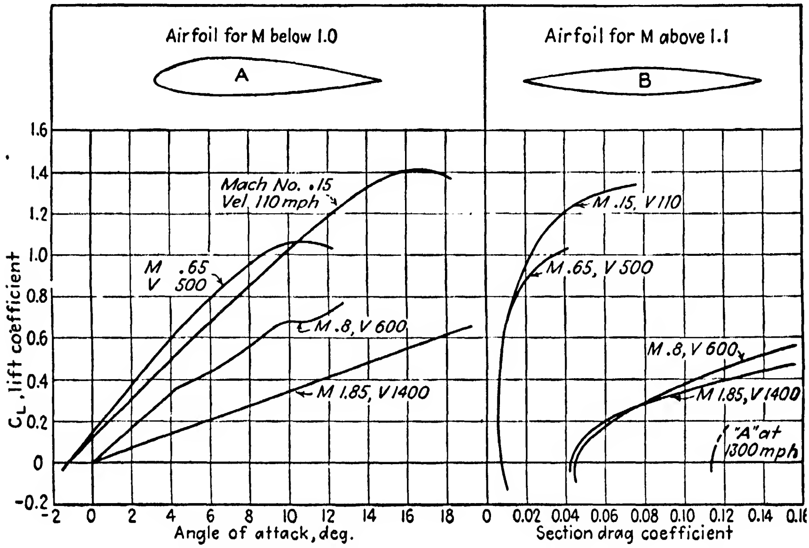


FIG. 27. Lift and drag coefficients for airfoils at several Mach numbers.

lift coefficient; next, to increase the drag coefficient even at low lift coefficients and shift the angle of zero lift to zero angle of attack. For the sharp-nosed supersonic airfoil, the drag coefficients at low lift coefficients are no larger than for the rounded-nose one at Mach number 0.8, but the lift coefficient at a given angle of attack is much less. The dotted line showing a drag coefficient about 0.11 is the probable drag coefficient of the rounded-nose airfoil at supersonic speed.

CHAPTER III

AIRFOIL MODIFICATIONS AND ARRANGEMENTS

In Chap. II some ideas about airflow and the characteristics of a typical airfoil were presented, but no reasons for choice of shape of an airfoil or plan form of a wing were given. Effects of shape changes on airfoil and wing will now be discussed.

A large variety of changes in shape of the cross section of an airfoil might be made. These may be separated into (1) changes in median-line camber; (2) changes in maximum thickness ratio; (3) changes in thickness distribution, *i.e.*, the thickness at any fraction of the chord in per cent of the maximum thickness and the location of the maximum thickness; (4) changes in shape of the median line including location of its maximum (see Fig. 28). The effect of these modifications have been shown best by tests made by the National Advisory Committee for Aeronautics. In the paragraphs that follow, general effects of the changes are given. In each case all shape factors except the one being discussed are unchanged.

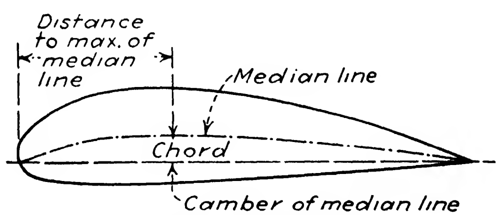


FIG. 28. Airfoil terms.

1. Camber is usually expressed in per cent of the chord. Camber controls the lift coefficient at which drag coefficient is a minimum. Thus for a plane that flies at high speed, low camber will be used, but for a plane that flies most of the time at a larger lift coefficient, an increase in camber will result in a lower profile drag coefficient. For extremely high speeds, zero camber has the advantage that the angle of zero lift does not change with Mach number. Increase in camber gives a desirable increase of maximum lift coefficient, but an undesir-

able increase in center-of-pressure movement and a small increase in minimum profile drag coefficient. Critical Mach number at any lift coefficient is slightly lowered by an increase in camber.

2. Maximum thickness is also given in per cent of the chord. Aerodynamically, thickness is harmful; it increases minimum drag coefficient somewhat, and it reduces critical Mach number. For supersonic wings the drag varies as the square of the thickness ratio; hence such wings must be very thin. Maximum lift coefficient is highest for airfoils 10 or 12 per cent thick. Center-of-pressure travel is not appreciably changed by thickness. The thickness is often determined by the requirements of the framework or *structure*. Thin wings will be excessively heavy unless fitted with external *bracing* of struts or wires. If the wing is externally braced, the drag of wing itself is reduced, but the sum of wing and bracing drag may be greater than if the wing were thick enough to be sufficiently strong without external bracing. Such an unbraced wing is called *cantilever*.

3. By skillful variation of thickness distribution, appreciable reduction in minimum drag coefficient has been made. The apparent differences between "low-drag" and other airfoils include: smaller radius at nose, maximum thickness moved back from 30 per cent of chord to 45 or 50 per cent of chord, and thin or hollow-ground trailing edge. Gains from the improvement of shape are lost completely unless surface is polished smooth. The smaller nose radius causes undesirable loss in maximum lift coefficient and increases abruptness of stall. Critical Mach number is increased slightly as maximum thickness is moved from 30 to 50 per cent of chord.

4. A major change in shape of median line results from variations of location of maximum ordinate. Usual location is 15 to 50 per cent of chord. If maximum ordinate is moved farther back, there is a rapid increase in maximum lift coefficient, but this is accompanied by such a large increase in minimum drag coefficient and center-of-pressure travel that such airfoils are not useful. Within the usual range, maximum lift coefficient and minimum drag coefficient change only slightly with maximum-camber location. Critical Mach number improves slowly as maximum camber moves back from 20 to 50 per cent of chord. Center-of-pressure movement becomes larger (less desirable) as maximum camber moves back. With a fixed position of maximum camber, making the rear part flatter than the front reduces the center-of-pressure travel, reduces slightly the critical Mach number, changes drag or lift little or not at all.

Choice of Airfoil. Since the shape and aerodynamic characteristics of

several thousand airfoils have been published, it is desirable to formulate some ideas to assist in deciding which to use on a particular airplane.

1. The thickness must be determined by the space to enclose the structure. The trailing edge must not be too thin.

2. The landing speed and total weight of the airplane are fixed. So from the lift equation [see Eq. (12) of Chap. II] the value of the product of $C_{L\max}$ and S may be determined.

$$C_{L\max}S = \frac{W}{q_{\min}} = B \tag{1}$$

This product is independent of the airfoil.

$$S = \frac{B}{C_{L\max}} \tag{2}$$

The wing area varies inversely with $C_{L\max}$.
The wing drag at any speed (dynamic pressure) is

$$D = C_D S q \tag{3}$$

$$D = \frac{C_D B q}{C_{L\max}} \tag{4}$$

Therefore the wing drag is lowest for any q with the airfoil for which $C_D/C_{L\max}$ at the C_L corresponding to that q is the lowest.

3. The travel of the center of pressure, usually measured as the change from maximum C_L to one-fourth maximum C_L, should be small.

4. If the airplane is to be flown at high speed, the critical Mach number should be high.

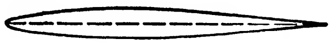
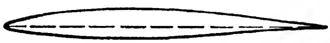
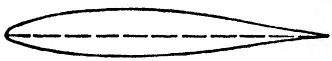
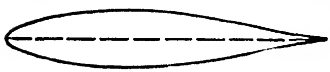
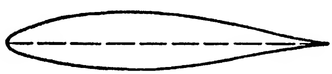
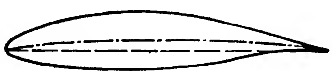
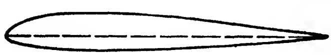
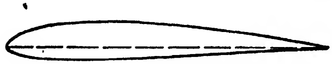
No one shape of airfoil gives the best solution for all these conditions. Generally good results are obtained by an airfoil with median line always concave downward, with amount of camber varied from none for extremely high speed planes to 2 or 3 per cent of chord for most planes and to 4 or 5 per cent of chord for planes designed especially for long-range flight, with the maximum ordinate of the median line at 45 or 50 per cent of chord and rear part of median line somewhat flatter than front part. About the median is placed the thickness, 10 to 20 per cent, agreed on by compromise with the structures group, with maximum thickness at 40 to 45 per cent of chord. Hollow trailing edges are not desirable.

Table 2 gives data on some typical airfoils and the sketches on it show the shape variations.

Changes in Plan Form. The wing may be modified, not only in shape of cross section, but also in plan form, *i.e.*, in shape as viewed from above. The size of wing needed for an airplane of known weight

and landing speed can be determined, as has been shown, from the lift equation [Eq. (12) of Chap. II]. What should be the relation between the span and the chord? The ratio of span to average chord is called the *aspect ratio*. To make the wing structure light we would like to use a low aspect ratio. Will this cause a lower or higher drag than if a high aspect ratio were used?

TABLE 2. AIRFOIL CHARACTERISTICS

Shape	NACA number	Max. thick., %	Max. C_L	Min. C_D	C.P. travel, %
	65-009	9	1.05	.0042	0
	65-209	9	1.26	.0040	8
	65-212	12	1.47	.0041	7
	65-215	15	1.52	.0043	7
	65-018	18	1.38	.0043	0
	65-218	18	1.47	.0046	6
	65-618	18	1.54	.0047	20
	23012	12	1.67	.0060	1
	2412	12	1.65	.0062	8

Data from NACA large scale tests; 65- are "low drag" airfoils; 209, 212, 215, 218 show effect of thickness; 018, 218, 618 effect of camber.

When producing a lift, the wing pushes downward a quantity of air. Consider a wing moving through still air; after it has passed, the air has a downward velocity. The kinetic energy of this air may be written as $\frac{1}{2}Mu^2/60 \times 32.2$, if M is the quantity in pounds per minute and u is the downward velocity imparted in feet per second. This energy is left behind; it must be supplied by the motion of the wing through the air. Therefore, power is required to push the wing through the air, and the wing suffers a drag which is called the *induced drag*. By Newton's second law of motion, the lift force is proportional to the change in momentum, Mu. The kinetic energy loss will be

least if M is large and u small, because it varies directly as M but directly as the square of u. The quantity will be large when the air density is high, when the wing is moving rapidly through the air, *i.e.*, when V is high, and when the span b of the wing is large. Aerodynamic theory, first expounded by Lanchester, Prandtl, and Munk following studies of airfoil shapes by Kutta and Joukowski, teaches that the quantity depends on the square of the span. We can write, remembering that L is lift and d is air density,

$$L \text{ depends on } Mu$$
$$M \text{ depends on } db^2V$$
$$KE \text{ depends on } Mu^2$$

The power used to move the wing is DV. The above quantities may be combined into one equation with a constant factor in it.

$$u = c\frac{L}{M} \tag{5}$$

$$DV = KE = \frac{C_1ML^2}{M^2} = C_1\frac{L^2}{M} = \frac{C_1L^2}{db^2V} \tag{6}$$

or, solving for D, the induced drag,

$$D = C_1\frac{L^2}{db^2V^2} \tag{7}$$

q, the dynamic pressure, is proportional to dV^2, so

$$D = C_2\frac{L^2}{qb^2} \tag{8}$$

and, from wing theory, C_2 is very nearly $1/\pi$ or

$$\text{Induced } D = \frac{L^2}{\pi qb^2} = \frac{W^2}{\pi qb^2} \tag{9}$$

since weight equals lift.

With the area S fixed, we obtain a large span with a high aspect ratio; therefore, wings of high aspect ratio are desirable to reduce the induced drag.

Consider as an example an airplane weighing 3,000 lb with a span of 30 ft. When the dynamic pressure is 100 lb (velocity about 200 mph), the induced drag is 32 lb, scarcely 1 per cent of the weight. But when the dynamic pressure is only 10 lb (flying about 60 mph), the induced drag is 320 lb, over 10 per cent of the weight. So it is very essential that the span or aspect ratio of slow-flying airplanes be large.

At the tips of a wing the excess pressure on the lower surface with the suction on the upper tends to make air flow from lower to upper surfaces. This forms an *eddy* or *vortex* at the tip which streams behind the airfoil as sketched in Fig. 29. The tip vortex may be seen nicely

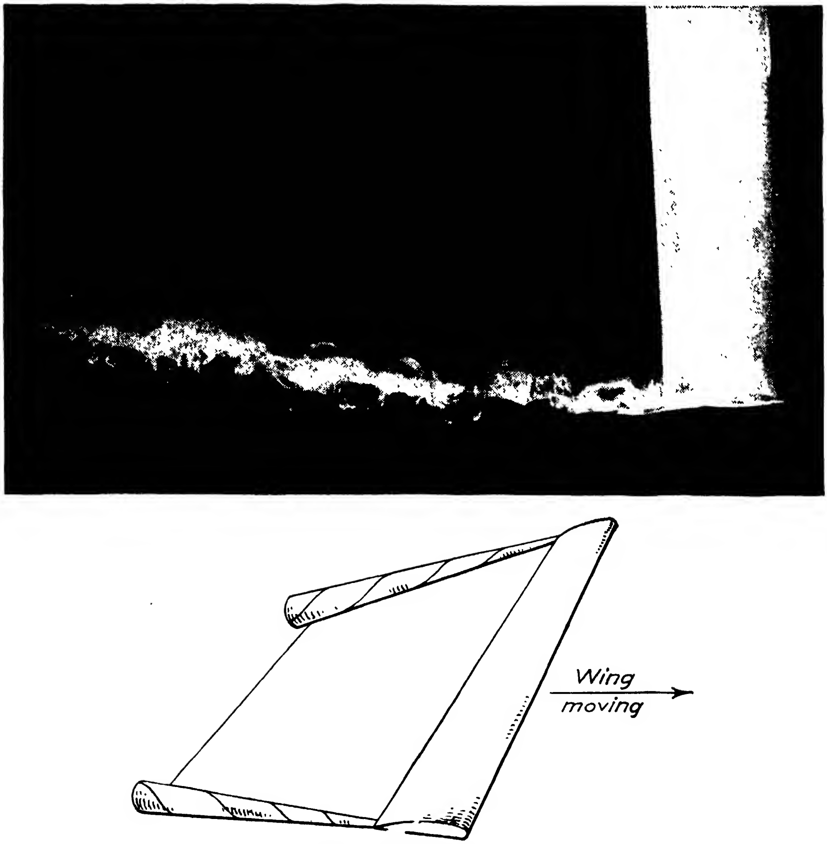


FIG. 29. Spiral vortices formed at wing tips.

if an airfoil-shaped stick is moved through smoke. Titanium tetrachloride forms a useful smoke to show airflow.

The induced drag is only part of the drag of a wing. The rest, the *profile drag*, is caused by the friction on the air moving along the wing surface and by the formation of an eddying wake behind the airfoil. The latter is not important at low angles of attack.

Some improvement in airfoil characteristics can be made by *tapering* the wings, *i.e.*, by making the chord shorter at the tip than at the cen-

ter. Tapering is beneficial only if kept within reasonable limits; a wing tapered to a point at the tip, for example, would have more drag than one with no taper at all. A tapered wing is lighter than one without taper, since the center of load is nearer the fuselage and the section at the fuselage is thicker.

Multiple Wings. The popularity of biplanes or other arrangements of more than one wing has varied. The earliest airplanes (1903–1907) were biplanes; then monoplanes became popular and were considered best (1907–1914). The pendulum swung back to biplanes (1914–1924), and again since 1926 monoplanes have gained favor. There are no biplanes now in production in this country.

Biplanes are advantageous if a small compact wing system is desired. The biplane structure, if externally braced, can be made lighter than the monoplane, but the external bracing adds to the total drag.

When two objects like wings are close to each other in an air stream, there will be an interference of each on the flow around the other. In a biplane this causes a reduction in lift, especially on the lower wing. The maximum lift coefficient may be 5 to 10 per cent lower for the biplane than for a monoplane of the same airfoil section. On the other hand, the quantity of air affected by the biplane is somewhat greater than that disturbed by a monoplane of the same span; therefore the induced drag of a biplane will be less than that of the monoplane if the total lifts and spans of monoplane and biplane are equal. The reduction is 10 or 20 per cent. It may more than offset the drag of the external bracing at moderate flight speeds. At high speeds the induced drag is low anyway, so the elimination of the drag of the external bracing gives the cantilever monoplane the advantage.

Variable Airfoils. The wing area is determined for an airplane of given weight and desired landing speed by the maximum lift coefficient. The drag of the wing at high speed varies directly as the area. It is pleasant, then, to imagine a wing whose area can be reduced for high-speed flight and increased to permit slow landing. But such a scheme is quite impractical. A better idea is to be able to change the shape of the airfoil in flight so that the maximum lift coefficient may be increased without a corresponding increase in the drag at high speeds.

It is sometimes incorrectly stated that a device permitting a variation in the *angle of incidence* between the wing chord and the fuselage would allow a lower landing speed; this is obviously wrong, since merely changing the angle of attack cannot affect the maximum value of the lift coefficient. The conventional airplane already utilizes the maxi-

mum lift coefficient of its wings during landing, so variable-wing-incidence devices are useless for reducing landing speed.

There are two general types of devices for increasing the maximum lift coefficient—*slots* and *flaps*.

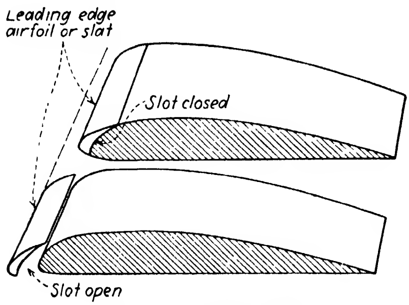


FIG. 30. Slotted wing.

Slots are passages through the airfoil near the leading edge (Fig. 30) from the lower to the upper surface. Air flowing through the slot to the upper surface delays the stalling of the wing to a higher angle of attack. The maximum lift coefficient is thus increased, as shown in Fig. 31. If such a slot in the airfoil were always open, the drag coefficient at low angles of attack would be increased as much, or even more, in percentage than would the maximum lift coefficient. To avoid this difficulty, Handley-Page in England and Lachmann in Germany developed a slot which is open at high angles of attack but which is closed at low angles of attack. They made the *leading-edge airfoil* or *slat* slide back and fit snugly against the main airfoil. This motion may be controlled by the pilot, but usually changes in air pressure on the slat itself are used to open and close the slot. When closed the slotted airfoil has very little more drag than the plain airfoil.

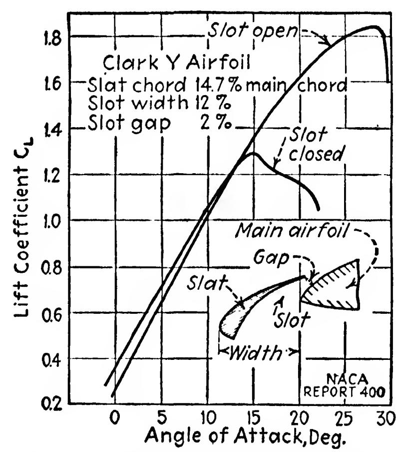


FIG. 31. Lift coefficient of a slotted and plain wing.

Flaps are hinged portions of the wing usually near the trailing edge. When turned down, the effect is to form a new airfoil with large median-line camber and with the highest point of that camber well back toward the trailing edge. Both of those factors make the maximum lift coefficient larger. Several kinds of trailing-edge flaps are shown in Fig. 32. With the *plain* or *slotted flaps* the entire rear portion of the airfoil is hinged; only the lower surface is moved on the *split flaps*. The *Fowler flaps* slightly increase the area of the wing in addi-

tion to acting as a flap. Flaps are operated by controls in the cockpit, on small airplanes directly by a lever or wheel, on larger airplanes by electric or hydraulic motors.

Usual practice is to use ailerons for lateral control and to fit the flaps only between the inner ends of the ailerons. Therefore, the flap seldom covers more than 60 per cent of the span of the wing, as on the airplane in Fig. 33, but tests show that the middle part is more

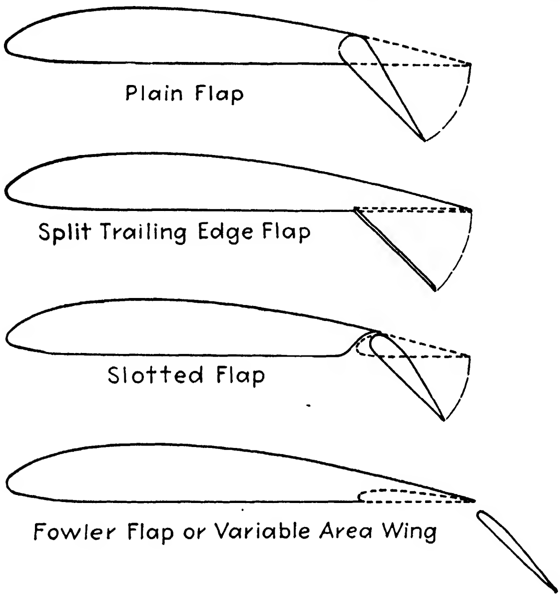


FIG. 32. Types of wing flaps (flap chord 25 per cent wing chord, flap angle 45°).

effective in increasing the lift. Almost all the high-speed transport air liners and most other high-speed planes are fitted with flaps. In the United States some military airplanes have been fitted with slots for increasing lift; on these flaps are used too. Slots are seldom used alone on an airplane. The stalling angle is so large that in order to land on main and tail wheels together, the landing gear must be very high. This delay of stalling caused by a leading-edge slot is utilized on numerous airplanes to prevent early stalling at the tips of tapered wings by fitting a short fixed slot near the wing tip. It is so short that the drag increase resulting is not important.

An old scheme for preventing early flow separation, hence low maximum lift coefficient, on thin wings has been revived for use on low-drag airfoils, of high critical Mach number, which have small leading-edge radii. This method is to fit a nose flap (Fig. 34).

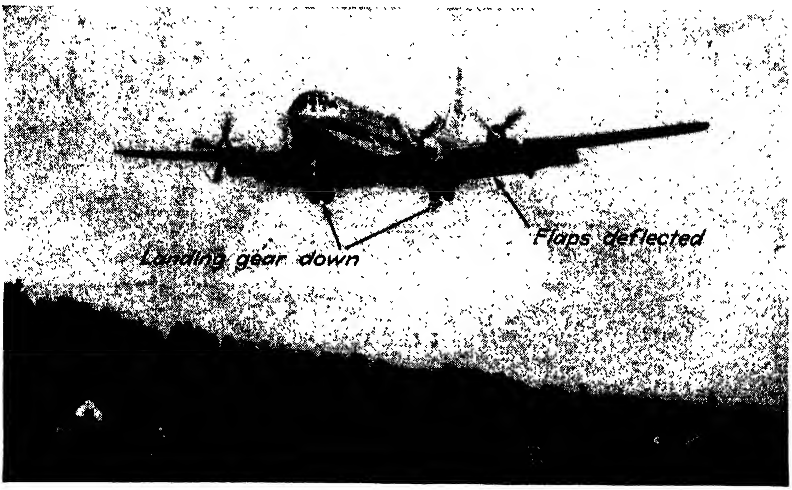


FIG. 33. Boeing Stratocruiser; flaps in high lift position. (*Boeing Airplane Company.*)

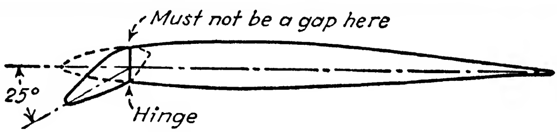


FIG. 34. Airfoil with nose flap.

Table 3 gives some characteristics of some types of flaps and slots.

TABLE 3. CHARACTERISTICS OF HIGH-LIFT WINGS*

Device	Maximum C_L	At maximum C_L	
		α, deg	C_D
Original airfoil	1.3	15	0.17
Plain flap, 30% at 45°	2.0	12	0.50
Split flap, 30% at 50°	2.2	14	0.52
Slotted flap, 30% at 50°	2.5	13	0.59
Fowler flap, 30% at 40° (increases area)	2.8	13	0.63
Handley-Page slot (sketched in Fig. 30)	1.8	28	0.44
Slot and flap, 30% at 50°	2.3	20	0.60

* These values obtained if flap or slot extends along entire span. Flaps usually cannot do so on the airplane. The usual increase is 70 to 80 per cent of those above. Data from NACA.

On high-speed airplanes the use of flaps or slots and flaps for landing has an additional advantage. The drag is much increased when the flaps are turned down. From the diagram of forces on an airplane when gliding without engine power (Fig. 35), the condition for equi-

librium of lift, drag, and weight is that the slope of the flight path should be D/L. Therefore, the use of the flap with high drag makes the flight path steeper, allows the airplane to land nearer an obstacle, as shown in Fig. 36, and generally makes the landing easier. Because

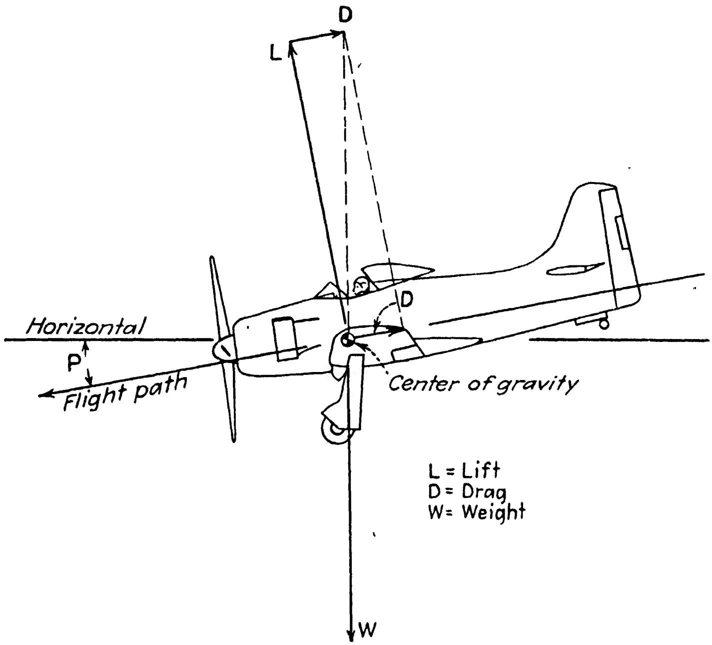


FIG. 35. Forces on airplane in glide.

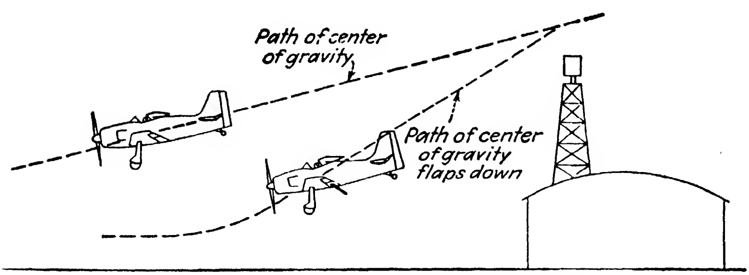


FIG. 36. Effect of flap on slope of flight path.

of their use for this purpose, flaps are sometimes called *air brakes*, but it should be remembered that increased drag due to the flap does not decrease the speed of the airplane but merely changes the steepness of the flight path, whereas the increased lift due to the flap does reduce the air speed.

CHAPTER IV

PARASITE DRAG

On the complete airplane the resultant air force may be divided into components. The lift, which is practically all supplied by the wings, is a useful force. Forces on the control surfaces and tail when used in directing the airplane are also useful forces. But the drag of all the parts is a useless force. The drag may be divided into two varieties: one, the induced drag, is paid for the lift; the rest is called the *parasite drag*. By present custom, the parasite drag includes the *section* (*profile*) *drag* of the wing, though sometimes the term is used for the drag of all parts of the airplane except the wing.

Parasite Drag. Parasite drag is the sum of the profile drag of the wing and the drags of fuselage, nacelles, if any, tail, wheels, and all other parts that project into the air stream.

Three causes contribute to the production of parasite drag: the impact of the air against the windward face of the body, the friction of the air sliding along its surface, and the formation of eddies in the air stream as it leaves the body. The resistance from this last source can never be entirely eliminated; often it can be reduced to reasonable proportions only with difficulty.

Naturally, the object of the airplane designer is to keep the parasite resistance just as low as possible, for every added pound of resistance demands an added pound of propeller thrust to overcome it and consequently an increase in engine power and in fuel consumption.

The total parasite drag of an individual part of a plane, except the wing, can be expressed in the form of an equation like that of the drag of an airfoil. This equation is

$$D_P = C'_{D_P} S' q \tag{1}$$

where D_P is the total parasite drag in pounds, C'_{D_P} is a drag coefficient, which, like the drag coefficient of an airfoil, depends upon the shape of the body, its attitude to the air direction, and if speed is high, the Mach number; q is the dynamic pressure corresponding to the air speed and density; S' is the *projected area* of the body in square feet. By projected area is meant the area of the largest cross section of the body which can be taken in a plane at right angles to the direction of the relative wind.

This equation shows that the parasite drag of a body is directly proportional to the dynamic pressure or the product of the air density and the velocity squared, just as are the lift and drag forces on an airfoil.

Effect of Shape on Parasite Drag. The shape of a body determines the relative magnitudes of the parasite drags from the three sources previously mentioned. If the body presents a flat surface in front, the impact resistance will be high; if it is long in the direction of the airflow, the frictional resistance is large; and if it is blunt at the rear, the eddy-making resistance is great.

As a sort of standard of parasite drag, it is convenient to consider, first, the flat plate set broadside to the wind. Evidently here the

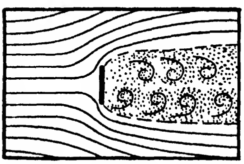


FIG. 37. Flow of air past a flat plate.

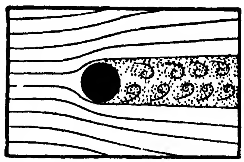


FIG. 38. Flow of air past a cylinder.

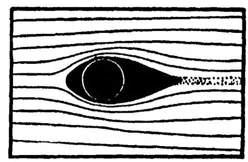


FIG. 39. Flow of air past a streamline section.

impact and eddy-making drags are large, and skin friction is negligible. For the square flat plate so placed, S' in the equation is the area of the plate in the ordinary sense. It has been found by numerous experiments that under these conditions the value of the resistance coefficient C'_{D_P} is 1.28, so that the drag of a flat plate 1 sq ft in area in an air stream moving at the rate of 100 mph would be about 33 lb. The drag changes somewhat with the shape of the plate, but these variations are not very great.

Figure 37 is a diagram of the flow past a flat plate and shows the sharp change of direction that the air must make in front and the extensive formation of eddies behind.

Around a cylinder, the flow, as shown in Fig. 38, is smoother. Impact and eddy-making drags are reduced, though skin friction is increased; the coefficient C'_{D_P} for cylinders of considerable length is 1.1.

Even around a cylinder, however, the flow of air is not by any means so smooth as might be desired, and a very marked reduction in drag may be made by adding material to the front and back, as shown in Fig. 39, converting it into what is known as a *streamline* section. The term *streamline* is employed because the air tends to flow past a section of this shape much more nearly in regular streamlines than it does past a section of any other shape. Though the greater length of the stream-

line body leads to a rise in skin friction, the resistances from the two other sources are so greatly diminished that there is a marked reduction in the total drag. For a good streamline section, the coefficient may be as low as 0.06, which means that the drag of a strut of this form would be only one-twentieth that of a strut of the same thickness but of cylindrical cross section.

A single round wire is a cylinder that has great length in proportion to its diameter, and it has about the same drag coefficient as any other long cylinder. A cable composed of a number of strands, in spite of its rough surface, does not differ much in drag from a cylinder of the same diameter. The high drag of single round wires has frequently caused them to be replaced by wires with the form of cross section shown in Fig. 40. These are known as *streamline wires*, although, since the curvature of the front is the same as that of the rear, the section is not a true streamline.

Fig. 40. Cross section of streamline wire.

In addition to bodies which, like struts, are very long in proportion to their thickness, it is necessary to consider also those that are solids of revolution, *i.e.*, bodies of which every cross section at right angles to the relative wind is a circle. The sphere is the simplest form of the solid of revolution, and its drag coefficient is 0.50 when the sphere is

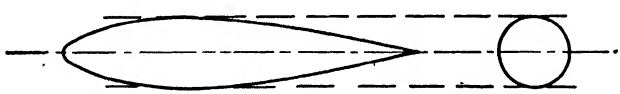


Fig. 41. Streamline body.

small and 0.10 when it is large. Again this resistance can be greatly reduced by fairing, and in this way the so-called *streamline body* is obtained. This has the form shown in Fig. 41. The drag coefficient of a streamline body depends upon its *fineness ratio*, the ratio of length to maximum diameter, and upon the size. For moderate sizes the lowest drag coefficient is about 0.04 for a fineness ratio of 3, increasing to 0.08 when the fineness ratio is 8. The drag is only one-thirtieth to one-fifteenth that of a normal flat plate of the same area. The drag is little more than that due to friction on the surface.

The better the form of a streamline body, the more its drag is increased by any slight irregularity in the surface. In practice the form of the ideal streamline body can only be approximated, since all airplane parts must necessarily have irregularities and projections from the surface.

All the drag coefficients given above were determined with the center line of the body in question pointing directly into the relative wind. If the angle between this axis and the relative wind is not zero, the drag is increased, largely because of the formation of more eddies. For small changes in angle, the increase is not very great. For example, a 5° angle for a streamline strut involves an increase in drag of 25 per cent, and the same angle for a streamline body gives an increase of 10 per cent. If the angle becomes large, however, the increase in resistance is great. In a streamline strut set at 15° to the relative wind, for example, the resistance is increased by 600 per cent over that with the axis at 0°.

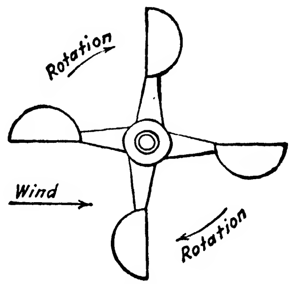


FIG. 42. Robinson cup anemometer.

Another form of body is worthy of brief mention in connection with parasite drag, because it has interesting application in another branch of aeronautics. This is the hollow hemisphere. If the concave side of the hemisphere is broadside to the wind, the resistance coefficient is 1.45, but if the other side is toward the wind, the coefficient is only 0.37. The Robinson cup anemometer, shown in Fig. 42, takes advantage of this difference. Three or four of these hollow hemispheres are mounted upon arms which rotate about a pivot, and the difference in resistance on the opposite hemispheres causes the device to turn at a rate that depends on the wind velocity. A parachute is also nearly hemispherical when in use; hence has a high drag coefficient.

Parasite Drag of the Airplane. The total parasite drag of the airplane is made up of contributions from many sources and, in fact, includes all the drag of the airplane except the induced drag. The profile drag of the wing is considered parasite drag.

The fuselage is a large contributor to this parasite drag. From the point of view of drag reduction, it would be desirable to make the fuselage in the form of a streamline body, but, on account of structural requirements, the necessity of carrying the useful load, and the need of affording proper vision to the pilot and passengers, the form of the fuselage can be only approximately that of a streamline body. The presence of open cockpits in the fuselage involves an addition to the parasite drag, as these and other openings disturb the airflow. Windshields, either for open or for closed cockpits, evidently constitute departures from good streamline shape and so cause increases in para-

site drag. Since strength must be provided to support the tail surfaces and to resist the shocks produced when the tail support strikes the ground, the rear of the fuselage generally cannot be tapered to the degree that would be desirable for keeping the drag at a minimum. The departures from streamline form lead to the production of eddies that add to the parasite drag. The drag coefficient of a good fuselage

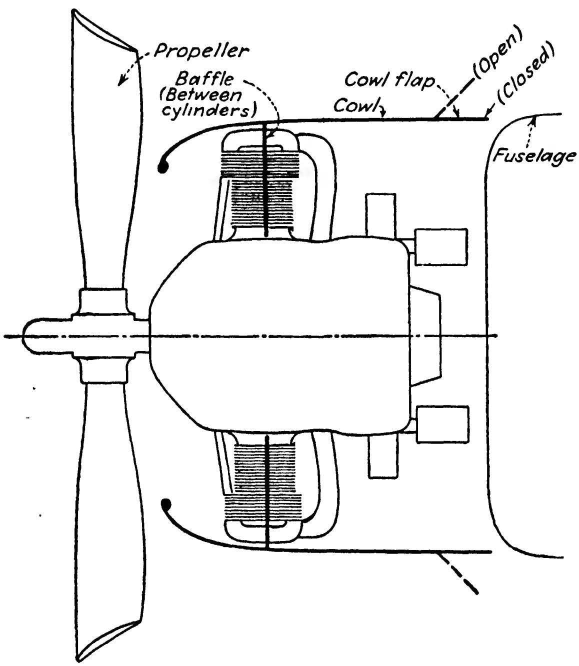


FIG. 43. Low-drag cowl (see also Fig. 94).

is only slightly greater than that of a streamline body; that of a poor fuselage may be three or four times as great.

More important is the departure from streamline form which arises from the presence of the engine. Even if a totally enclosed water-cooled engine is installed, it usually requires the nose of the fuselage to have a shape different from that of the perfect streamline body. In addition to this, such an engine requires a radiator, which adds to the parasite drag. If an air-cooled engine is used, even though it is well cowled, there will be a marked increase in parasite drag, due partly to the resistance of the cylinders to the air that must flow over them for cooling and partly also to the general disturbance of the airflow over

the fuselage which necessarily results from the installation of the engine.

Researches at the Langley Memorial Laboratory of the National Advisory Committee for Aeronautics led to the development of low-drag cowls for radial air-cooled engines by which the additional drag due to the engine is reduced to one-third of what it would be without this special cowling. Figures 43 and 44 show the type of low-drag cowl first developed by the NACA.

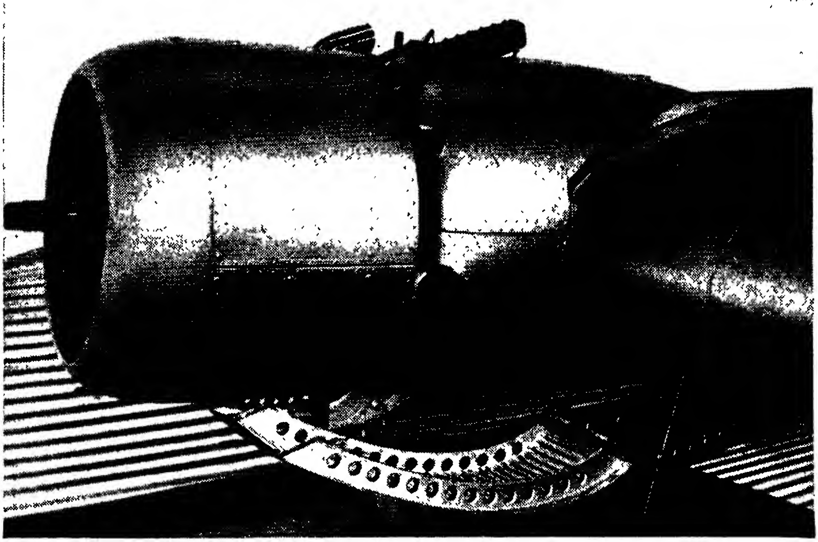


FIG. 44. NACA cowl on radial engine. (*The Glenn L. Martin Company.*)

The low-drag cowl reduces the parasite drag of the combined engine and fuselage, partly by restricting the flow of the cooling air to that which is just sufficient to keep the engine temperature from rising too high and partly by compelling the air to flow around the nose in such a manner as to minimize the formation of eddies along the side of the fuselage behind the engine.

Baffles of sheet metal are fitted around and between the engine cylinders and heads to make certain that all the air flowing through the cowl actually contributes to the cooling. To regulate the airflow to the minimum for all flight conditions, *cowl flaps* are fitted at the exit of the cowl. For flat opposed-cylinder air-cooled engines, cowls to assist cooling and reduce drag are similar to those used on radial engines (Fig. 45).

Turbojet or turboprop engines require no external cooling fins or radiators, hence add less to the parasite drag than reciprocating engines. Airscoops for such engines must be carefully located to avoid excessive penalty in parasite drag (Fig. 1, page 2).

The landing gear is also an important source of parasite drag. This landing-gear drag may be reduced by *streamlining*, *i.e.*, by giving all parts a shape as nearly as possible that of the streamline section already

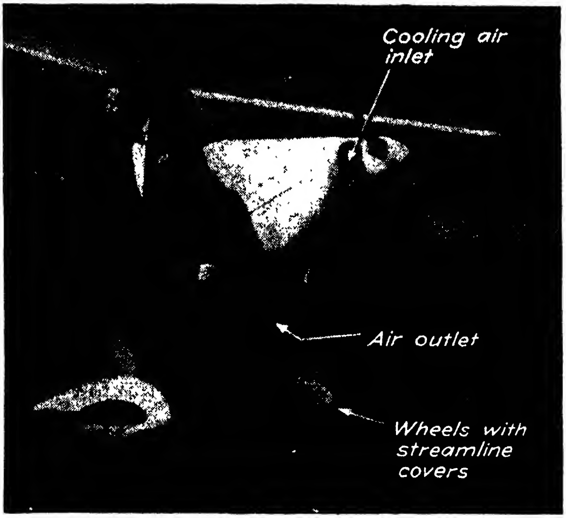


Fig. 45. Cowl for opposed engine and streamline landing gear on Super Chief. (*Aeronca Aircraft Corporation.*)

described. A landing gear in which the parasite drag has been reduced by this method is illustrated in Fig. 45. A further step in the reduction of landing-gear drag is to make the gear partly or wholly *retractable*, *i.e.*, to design it so that when the airplane is in flight it may be partly or entirely withdrawn inside some other part of the machine. Such a landing gear is shown extended in Fig. 46 and retracted in Fig. 47.

The contribution of the tail surfaces to the parasite drag is not very large unless the surfaces have extensive gaps between them or require an undue amount of external bracing.

Of the total parasite drag the wing contributes about 30 or 40 per cent, unless the plane is a *flying wing* without fuselage or tail. This contribution may be kept to a minimum by selecting an airfoil with small section or profile drag coefficient (this has been discussed in Chap. III) and by eliminating external bracing. In some small air-

FIG. 46. Retractable landing gear in extended position. (*Chance Vought Aircraft.*)

FIG. 47. Retractable landing gear with wheel up. Note that wheel turns 90° as it retracts. The gear is shielded with covers. (*Chance Vought Aircraft.*)

planes the added drag of such bracing is accepted as a penalty to offset the lighter, possibly more easily built structure that is permitted if external bracing is used. More generally the weight penalty is accepted as less than the drag penalty.

A test of a model usually shows that the drag of the complete airplane is more than the sum of the individual drags of all the separate parts. This phenomenon arises from disturbances in airflow which

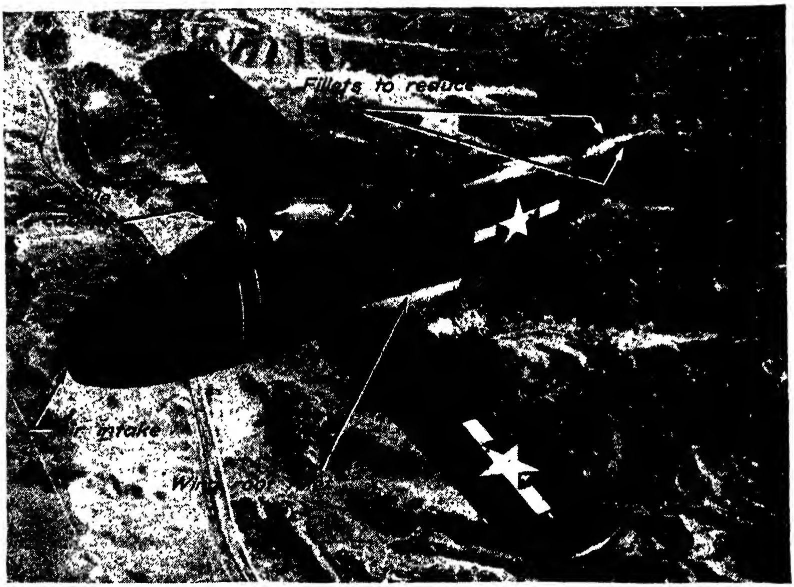


Fig. 48. Low-drag turbojet fighter FJ-1 Fury built by North American. (*Official U.S. Navy photograph.*)

produce an effect known as *interference*. There is, for example, an interference between the fuselage and the wings, as well as between the struts and the fuselage. Where two struts intersect, particularly if the angle of intersection is small, there is likely to be a considerable interference drag. This often is the case in landing gears, where structural considerations frequently require that two or more members join at very acute angles. Interference between wings and fuselage is reduced by *fillets*, or curved sections where the wing and fuselage meet (Fig. 48).

The obvious means of reducing interference drag are (1) making the number of different parts as few as practicable and (2) giving all those exposed to the air a streamline shape. Of conventional planes, the cantilever monoplane approaches nearest to this ideal. Figure 48

shows such an airplane with parasite drag further reduced by fillets, by completely retracting the landing gear, by a bubble canopy, by very smooth surfaces, and by omission of cooling drag since it is a jet-engined plane. Further reduction can be made by omitting the fuselage in a *flying wing* (Fig. 49).

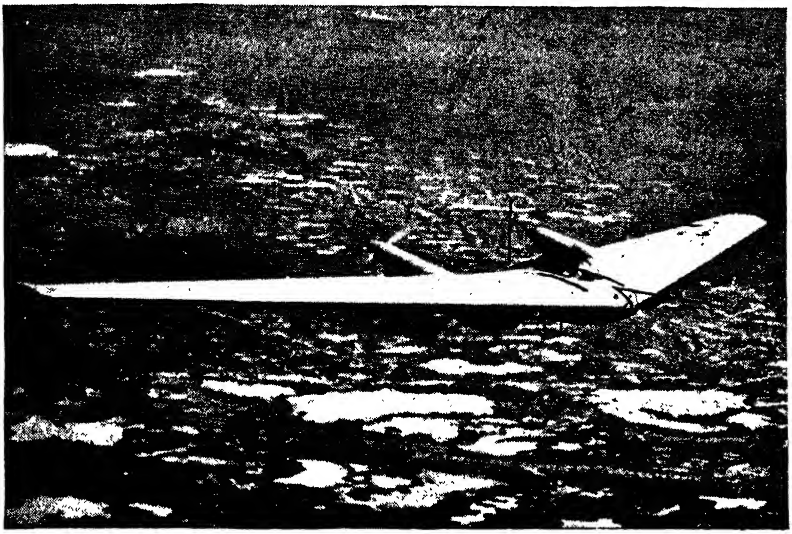


FIG. 49. Flying-wing training plane N4M. (*Northrop Aircraft, Inc.*)

Often the total parasite drag of an airplane is expressed by a drag coefficient C_{D_P} defined by

$$\text{Total parasite drag} = C_{D_P} \times \text{wing area} \times q \qquad (2)$$

Values of C_{D_P}, including wing profile drag, are:

Flying wing	0.010
Conventional airplane	
Exceptionally low	0.013
Very low	0.020
Low	0.025
High	0.045

Airplanes to be considered of exceptionally low parasite drag will have cantilever wings, small and well-shaped fuselages, landing gears that retract smoothly into wing or fuselage, few or no excrescences, surfaces very smooth, engine well cowled. Examples of such planes are some fighters or bombers with turbojet engines or possibly air- or liquid-cooled reciprocating engines. Most fighters and small bombers vary from very low to low. Transports are low or slightly poorer.

CHAPTER V

STABILITY AND CONTROL

Stability may be defined broadly as that characteristic of an airplane by virtue of which it flies in a straight path of its own accord. An airplane which does this is said to be *stable*, and one which does not is *unstable*. If a stable airplane is momentarily disturbed, as by a side gust of wind, it tends to return of itself to its original equilibrium attitude; the unstable machine has no such tendency, but must be brought back to the original attitude by the pilot.

Control is the action that the pilot takes to make the airplane follow any desired course, and an airplane is said to be *controllable* when it responds easily and promptly to movements of the control levers.

Stability and *controllability* do not necessarily go hand in hand. It is quite possible for an airplane to be highly controllable and yet to have little stability.

The action of a caster on a piece of furniture rolling along the floor is a convenient illustration of stability in a moving body, for the wheel of the caster tends always to trail directly behind the vertical pivot to which the caster is attached, so that the caster as a whole maintains a constant attitude with respect to the direction of motion. If displaced by hand it will promptly swing back into its original position. If it were set with the wheel exactly in front of the pivot, it would be in equilibrium, but it would not maintain this attitude in motion after even the least disturbance but would promptly return to the original attitude with the wheel behind. At any other attitude the caster would not be in equilibrium, but would move to the stable equilibrium point.

Since stability and controllability are characteristics of an airplane in motion, it is necessary, before continuing the discussion of these topics, to consider the possible motions of an airplane. An airplane may move in an infinite variety of ways, but no matter how complicated, it is possible to break down or resolve the motion into *components* consisting of three *linear* motions along mutually perpendicular axes, and three *angular* motions about the same axes.

A linear motion is one in a straight line, and when the airplane has only linear motion, every part of the machine moves at the same speed,

and the directions of motion of all parts of the machine are parallel. The motion of a railroad train on a straight track is an illustration of the simplest sort of linear motion, for while the train can move either forward or back, each of these motions is in the same straight line. The train is then said to have only one possible linear motion. A piece of furniture rolling on a level floor has two possible linear motions, for not only can it go forward or back like the train, but it can also go to the right or left. It can move parallel to either of two lines, at right angles to each other, such as a north-south line and an east-west line. Motion along a diagonal line, such as northwest, may be considered as the result of a motion to the north combined with one to the west. The north and the west motions are *component* motions, while the northwest motion is the *resultant* of the two components. The airplane has the two possible linear motions of the piece of furniture and also a third one, vertically up or down, *i.e.*, the airplane has three possible component linear motions.

In discussing angular motions, the most convenient example is that of a ship on a rough sea, for the ship can have three angular motions. The first of these angular motions or rotations is a turn to the right or left, during which the ship rotates about a vertical axis. This may or may not be accompanied by linear motion. Usually it is, but it is quite possible to imagine a twin-screw steamer being turned at a standstill by backing on one propeller and going ahead on the other. The two other angular motions of a ship are *rolling*, a rotation from side to side about a fore-and-aft axis, and *pitching*, a rotation about a horizontal axis across the ship, so that when the bow is rising the stern is descending, and vice versa. As some unfortunate passengers know only too well, all three of these angular motions may occur simultaneously, but, just as any linear motion may be considered the resultant of two or three independent linear components, so any angular motion may be considered as the resultant of two or three independent angular components. The airplane evidently can pitch and roll just as a ship does. It can, of course, turn to the right or left also, and this last motion is called *yawing*.

Since the airplane in flight is a free body, *i.e.*, one that is not restrained by a track, held down by gravity on a flat surface, or supported in solid bearings, it will always rotate about its *center of gravity*. This center of gravity is the point at which the airplane could be hung by a single rope and still be perfectly balanced in all directions. This center has no actual physical existence, but it is a perfectly definite concept in the mind of the aeronautical engineer and is usually indi-

cated on his drawing of an airplane. The three mutually perpendicular axes about which angular motion can take place then intersect at the center of gravity, and these lines are also the directions of the three possible linear motions. The axes and the directions of the corresponding motions are shown in Fig. 50.

Longitudinal Stability and Balance. An airplane is said to possess longitudinal stability when it has a tendency to keep a constant angle of attack with reference to the relative wind, *i.e.*, when it does not tend to put its nose down and *dive* or to lift its nose and *stall.* Longitudinal stability, therefore, refers to motion in pitch. In a simple longitudinal

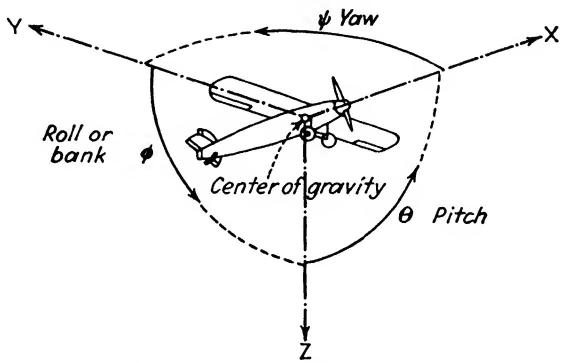


FIG. 50. Airplane axes. (*National Advisory Committee for Aeronautics.*)

motion the center of gravity of the airplane moves in one vertical plane.

The angle of attack at which the airplane is in equilibrium and which it tends to maintain constant in flight if it is longitudinally stable is called the *angle of trim.* Since a definite airplane speed corresponds to each angle of attack, a certain speed will correspond to the angle at which the airplane balances; this speed is called the *trimming speed.*

At the angle of trim the moment of the air forces about the center of gravity is zero. Just as the drag of the airplane is the sum of the induced drag, the wing profile drag, the fuselage drag, etc., so the moment is the sum of contributions from all the parts. For the moment, the principal parts are the wing and the tail. In Fig. 51 lift forces on wing and tail and weight are shown for a typical airplane in high-speed flight. The equilibrium corresponds to equilibrium of a lever with the fulcrum corresponding to the center of gravity.

If the airplane is not unstable, the moment change due to a momentary (not-in-equilibrium) change of angle of attack must try to restore

the original angle; *e.g.*, if the angle of attack becomes larger than the trim angle owing to flying into a "bump" or gust, a diving movement must result (Fig. 52).

The contributions of the wing will be unstable if the center of gravity is back of the quarter chord. For a horizontal tail back of the wing,

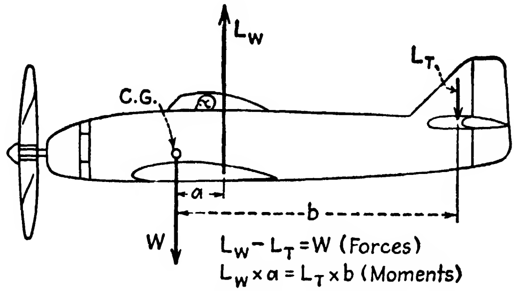


FIG. 51. Equilibrium of airplane.

the lift on the tail becomes more positive (or less negative) if the angle of attack is greater than the angle of trim; hence the tail contributes a diving moment about the center of gravity. This is a stabilizing moment and must be large enough to overcome the unstable moment of the wing and other parts, such as fuselage or nacelle.

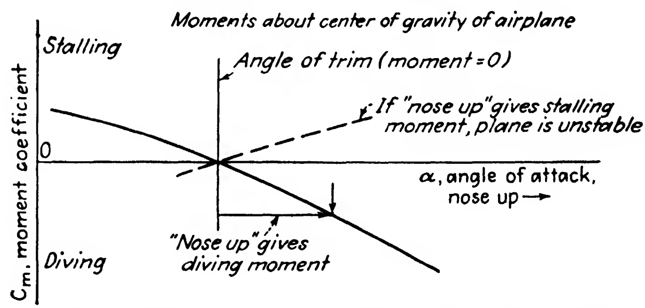


FIG. 52. Variation of moment coefficient with angle of attack.

On the other hand, if the center of gravity of the airplane is ahead of the quarter chord of the wing, the contribution of the wing will be stabilizing. Hence on a flying wing or other tailless airplane the center of gravity must be located ahead of the quarter chord of the wing in order to prevent the plane from being unstable. In order that the flying wing may be trimmed with the center of gravity ahead of the quarter chord, the trailing edge of the wing must be slightly turned up (or reflexed), or movable controls on the trailing edge must be set with trailing edge raised.

From a casual inspection of the horizontal tail surfaces on a conventional airplane, it would probably not be apparent that they carry down load in ordinary flight, for they appear to be set at the same angle to the longitudinal axis of the airplane as are the wings. The wings, however, are working in undisturbed air, while the tail surfaces are operating in the air which has previously passed over the wings. From the phenomenon of downwash already discussed, it will be apparent that the air which strikes the tail surfaces has a downward angle with respect to the longitudinal axis of the airplane. This is illustrated in Fig. 53, from which it is evident that the horizontal tail surfaces are really acting at a negative angle of attack with reference

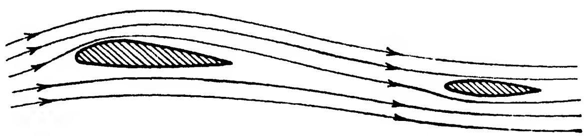


FIG. 53. Effect of downwash on horizontal tail surfaces.

to the local direction of the air which strikes them and that, therefore, they are exerting a downward rather than an upward force.

If an airplane has enough longitudinal stability, it will not go into a stall if the engine fails. Suppose the airplane is flying in a level path in equilibrium and the engine suddenly stops. The first effect upon the airplane is a decrease in its forward speed. This leads to a decrease in lift, and with the lift less than the weight, the airplane begins to settle, so that the flight path, instead of being level, as before, is inclined downward. Since the direction of the relative wind is always that of the flight path, this means that the relative wind, instead of blowing level at the airplane, is now blowing somewhat upward. The angle of attack is increased, and the stabilizing action of the horizontal tail surfaces comes into play to readjust it to about the same value relative to the flight path which it had before the engine failed. As the flight path now slopes downward, some of the airplane weight acts along it to supply a pull which makes up for the loss of propeller thrust. As long as this pull along the flight path is insufficient to compensate completely for the loss of propeller thrust, the airplane will tend to lose speed, but each loss of speed leads to a readjustment to a steeper angle of flight path, and this continues until the airplane is gliding at about its original equilibrium speed.

The stabilizing action of the horizontal tail surfaces is effective also in correcting the attitude of the airplane to compensate for an increase in engine power. If, while the airplane is flying level and in equilib-

rium, the throttle is opened wider, the first effect is an increase in airplane speed, and this leads immediately to an increase in the lift to a value greater than the weight of the airplane. The airplane starts to rise, and the relative wind now blows upon it somewhat from above. This decreases the angle of attack, but the action of the tail surfaces is such as immediately to increase it again, so that once more the airplane reaches its angle of equilibrium with respect to a new flight path. This time, however, the flight path is inclined upward.

In the discussions of the three previous paragraphs, no consideration has been given to the action of the *slipstream*, the blast of air which is driven backward by the propeller. This modifies the lift of the tail surfaces which work in it and so has a distinct effect upon the stability of the airplane. The effect, however, is usually one of degree only, and the statements made above are still true to a fair approximation. Usually the equilibrium speed of the airplane in the glide would, however, be somewhat greater than that in level flight, and that in climb would be less.

Control in Pitch. So far it has been assumed that both stabilizer and elevator remain fixed with regard to the fuselage. As long as this is true the airplane will fly at only one air speed or at slight variations from it due to the slipstream. If the pilot wishes to fly at another speed, the angle of trim must be changed by moving the elevators.

The combination of stabilizer and elevators acts like an airfoil with a flap on its trailing edge. If the trailing edge of the elevator is moved up by the pilot, the lift on the tail becomes more negative, pitching the plane to a larger angle of attack at which it can support itself at lower speed. If the trailing edge of the elevator is moved down, the lift on the tail becomes less negative (or more positive), raising the tail and making the airplane fly at a higher air speed. The trimming speed is lower with the elevator up and higher with it down. Usually the airplane will have less drag at lower speeds; thus, to fly level at different speeds, the pilot must adjust the throttle of the motor as well as move the elevator. But, fundamentally, the elevator angle fixes the angle of attack and, in turn, the flight speed, while the use of the throttle determines whether the plane will climb, fly level, or glide.

If the plane flies with different loads of fuel, cargo, or passengers, the center of gravity will not always be at the same point. Suppose a plane was trimmed at 150 mph with no force on the elevator control (the case when the elevator is nearly in line with the stabilizer); then some of the passengers move to the back of the cabin, which moves the center of gravity back. To fly at 150 mph, "down" elevator would

be required and the pilot would call the plane "tail heavy." If the passengers moved forward, "up" elevator would be needed, and the plane would be "nose-heavy." To balance changes in center of gravity and to fly at different speeds, the elevators may move to large angles from neutral, and a large force may be required to move them. To avoid this the trimming speed may be changed by changing the angle between stabilizer and fuselage, or a *trimming tab* may be used. This is a small flap on the trailing edge of the elevator, which may be adjusted by the pilot to make the neutral (no-control-force) angle of

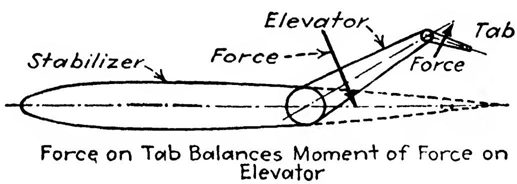


FIG. 54. Action of elevator trimming tab.

the elevator other than in line with the stabilizer (see Fig. 54). The The tab is adjusted by the pilot to give the required elevator angle.

Longitudinal Motion. If a longitudinally stable airplane is disturbed by flying into a "bump," it returns to its former speed and altitude along an undulating path, just as an automobile after hitting a bump in the road rocks back and forth and rises and falls. It is very desirable in both cases that the motion should subside rapidly. The airplane does three things: it pitches, it rises and falls, and its speed along the path varies.

The tendency to pitch is opposed by the change in moment of the force on the tail. As the plane pitches—say, increases the angle of attack—the tail has a downward velocity, which, combined with the forward speed, increases (positively) the angle of attack of the tail and adds an up load. An up load on the tail tries to dive the airplane and so tends to stop the pitching.

The tendency to rise or fall as the airplane flies along is opposed by the lift on the wings. Suppose the plane rises; the upward velocity combined with the forward speed makes the angle of attack of the wings less; hence the lift is less and there is in effect a downward force. This operates to stop the plane from rising.

The tendency to gain or lose speed is opposed by the change in airplane drag which the speed change would cause. The drag varies as V^2, so an increase in speed increases the drag; and the increased drag

pushes back to retard the plane. In this way the drag tends to prevent the changes in speed.

These three effects opposing pitching, rising or falling, and speed changes are called *dampings*. At high speed a small change in angle of attack means a big change in speed, so the damping due the drag is most important; at speeds near the minimum a large change in angle means only a small change in speed and the damping due to the tail is important.

Lateral Stability. It has been seen that in pitching motions the center of gravity moves in one plane. Motions in which the center of gravity does not remain in one plane are called *lateral*, and the tendency to return to original attitude from such motion is *lateral stability*. Usually the motions considered are *rolling*, *yawing*, and *sideslipping*, the longitudinal effects being excluded. Sideslipping means just what it says—it corresponds to skidding in an automobile and is sometimes called *skidding*.

It is not possible to speak separately of the rolling and yawing motions since one always involves the other. If the airplane has a yawing motion, one wing tip travels faster than the other; the lift varies as V^2, so the lift on that tip is larger, and it rises, giving to the airplane a rolling motion. The drag on the faster moving tip is also larger—it too varies as V^2—so there is a force tending to retard the faster moving tip—a damping of the yawing motion. But suppose the airplane had a rolling motion; as it flies along one wing tip is dropping. The downward velocity combined with the forward speed increases the angle of attack on that wing tip, and the angle on the opposite one is reduced. Unless the increased angle of attack is so large that the wing stalls, the force component parallel to the flight path on the dropping tip is reduced and that on the rising tip is increased, so a yawing motion results. The lift at the larger angle is increased, unless the wing stalls, so there is a force tending to prevent the wing from dropping—a damping of the rolling motion. If the dropping wing stalls, the lift force on it is reduced and, in place of the damping, a moment to increase the rolling motion results. Simultaneously a vicious yawing motion is caused. The pilot will have difficulty in controlling the airplane if rolling at large angles of attack is not promptly checked.

Thus a yawing motion produces a rolling motion, and a rolling motion causes a yawing motion. A sideslip tends to produce both a rolling and a yawing motion. The yawing should be such as to turn the airplane into the direction in which it is slipping. This is sometimes called *directional stability*. The fuselage alone is unstable, so a

vertical tail is needed. Usually there is a fixed fin and a rudder hinged to it, as shown in Fig. 55.

The effect of the sideslip is the same as if the airplane were yawed to the wind direction as shown on Fig. 56. The vertical tail obviously gives a force to turn the airplane into the wind direction, as is desirable. The rolling motion resulting from a sideslip should be such as to raise the forward wing tip (*A* in Fig. 58). The desired rolling moment is generally obtained by using *dihedral angle* in the wings. The amount varies from 1 or 2° on biplanes or high-wing monoplanes up to 7 or 8° on some low-wing monoplanes. Figure 57 shows how the sideslip combines with the forward velocity to give an angle of yaw and a diagonal flow across the wings. If the wing has dihedral, the flow on the forward wing goes from a higher point on the leading edge to a lower point on the trailing edge, as shown by Fig. 58, while on the trailing wing the flow is from a lower point on the leading edge to a higher point on the trailing edge. This results in an increase in angle of attack of the forward wing rela-

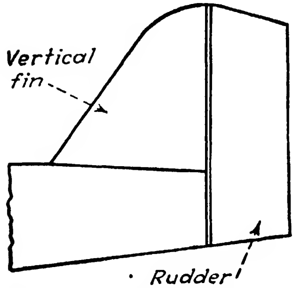


FIG. 55. Vertical fin and rudder.

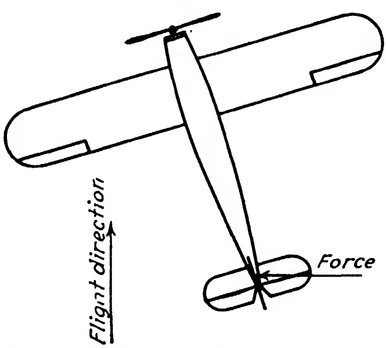


FIG. 56. Force on vertical tail surfaces in yaw.

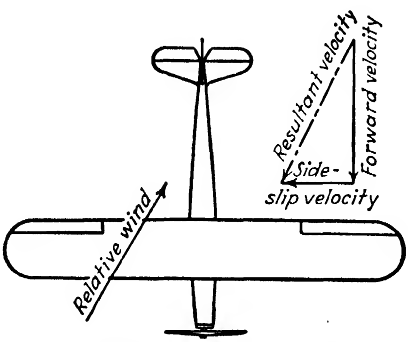


FIG. 57. Effect of sideslip on direction of relative wind.

tive to that of the rear one. A difference in angle means a difference in lift on the two sides of the plane, and hence the desired rolling moment is obtained.

The airplane cannot be laterally stable unless it yaws into a sideslip and rolls out of a sideslip. It may not be stable even if it does both these things.

As explained, the rolling motion is damped by the changes of lift on the wings; the yawing motion is checked by changes in drag on the wings. The yawing motion is also damped by the vertical tail in a manner analogous to the damping of a pitching motion by the horizontal tail. When the plane sideslips, it flies yawed, and there is a

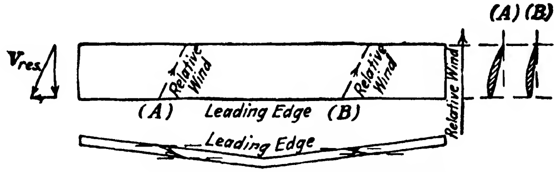


FIG. 58. Action of dihedral in sideslip.

side force that tends to retard the sideways velocity. This damping force comes largely from the fuselage and tail surfaces.

Directional Control. To make the airplane fly in a curved path, a side force must be applied. Turns of long radius may be made to the right by holding the trailing edge of the rudder to the right ("right rudder"). The moment of the force on it holds the plane at a small angle of yaw to the right, and the side force on the fuselage curves the flight path to the right. This is the way, and the only way, a steamship turns. In the airplane there is a much larger force available, which, if used, will make turns of shorter radius. That is the lift. To use it for a right turn, the airplane must be banked to the right, *i.e.*, right wing down. The bank may be very steep so that the wings are nearly vertical. The lift remains perpendicular to the span of the wings. When the plane is banked, the lift may be divided into two components (Fig. 59): the vertical one must support the plane and so must be equal to the weight; the horizontal one curves the path of the plane and is equal to the centrifugal force. The steeper the bank, the larger will be the horizontal force and the sharper the turn.

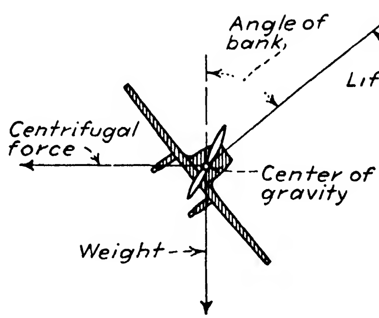


FIG. 59. Forces in a steady turn.

The plane may be banked by the rudder, the ailerons, or, as is usual, by both. If sharp turns are attempted by using the rudder, the first effect is a yawing and outward skid. The outer tip travels faster than

the inner; thus it has more lift and banks the plane. The skid adds to the rolling moment if the wings have dihedral. So the plane banks and the turn is made. To prevent too steep banks, the pilot must use his ailerons or sideslip inward. The ailerons on the wing tips are flaps whose control is usually so connected that, as one trailing edge moves down, the other moves up, though not necessarily the same amount. The lift is increased on the down side and reduced on the up side, so a rolling moment is produced. This rolling moment can be used to bank the airplane to make a turn. In order to turn without slipping inward or skidding outward, both rudder and ailerons are used.

Rolling Control. The ailerons are used also to maintain the wings level transversely in straight flight. If one wing tip runs into a "bump," usually a rising air current, its angle of attack will be increased, its lift will increase, and it will rise, rolling that tip of the plane up. The rolling moment of the ailerons is used to offset that due to the bump. The rolling moment of the ailerons is due to differences of lift on the two; unfortunatley in most cases there is also a difference in drag on the two, which causes a yawing moment. The yawing moment is balanced by moving the rudder. The control is satisfactory until, on the down-aileron side, the wing tip stalls; the lift difference, and hence the rolling moment, becomes much smaller, while the yawing moment becomes very much larger. The direction of the yawing moment is to pull back the wing which the aileron is trying to raise. If a yawing velocity is allowed to start, the higher outer wing tip travels faster and rolls the inner lower wing tip even farther down. The rudder may be used in place of ailerons, giving a yawing velocity in the opposite direction so that the low wing travels faster and rises. The adverse yawing effect of the ailerons may be reduced if the up aileron moves through a larger angle than the down aileron. Serious trouble arises if the low wing tip stalls. This may be delayed to a higher angle of attack if Handley-Page slots are fitted at the tips only. When so used, the slot operates automatically, and neither tip stalls until after the rest of the wing.

Sometimes, to help the ailerons, a *spoiler* is used (Fig. 60). This moves out as the aileron comes up. It spoils the lift and increases the drag on the higher side so that the plane rolls toward an even keel and also tends to yaw to bring up the low wing tip. The difficulty with spoilers has been that the reduction in lift is delayed, *lags*, so that the response is too slow; this lag is minimized by locating the spoilers as close to the trailing edge as the aileron or flap permits. On several

airplanes flaps have extended almost to the wing tips (thus increasing the maximum lift coefficient) with small ailerons at the tips operated in conjunction with spoilers, or *retractable ailerons*, located in front of the flaps. The small ailerons help eliminate lag of spoilers and also give to the pilot the control-force *feel* to which he is accustomed. This system was introduced on the Black Widow P-61.

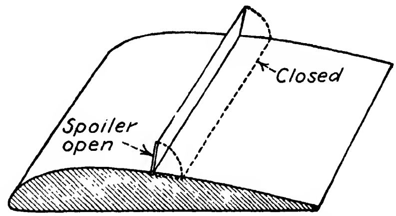


FIG. 60. Spoiler on a wing.

Control-operating Mechanism. A typical airplane control system is shown diagrammatically in Fig. 61. The rudder is operated by the pilot's feet, either with a rudder bar or by means of pedals. The rudder bar is the simpler arrangement, but pedals have the advantage of requiring less width in the fuselage and are of easier adjustment to suit pilots of different size. From the rudder bar or pedals, two cables

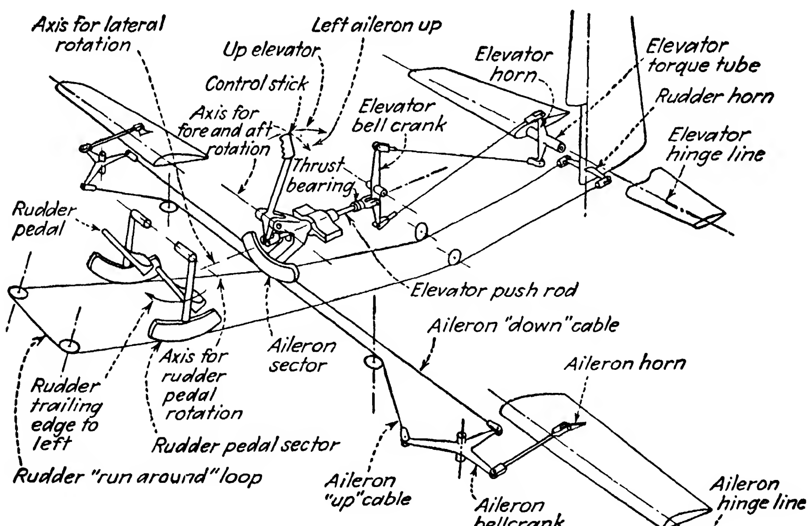


FIG. 61. Diagrammatic sketch of typical airplane control system.

lead back to short masts or *horns*, one on each side of the rudder. Since the cable from the left side of the rudder bar, or from the left pedal, as the case may be, leads to the horn on the left side of the rudder, it is apparent that, when the pilot pushes with his left foot, the trailing edge of the rudder will move toward the left and the air-

plane will turn to the left. This action, it should be noted, is the opposite of that of the corresponding control on a bicycle or a bobsled.

In the simplest arrangement, the control cables from the horns on the elevator and from those on the ailerons are connected to a movable vertical member called the *control stick* in the pilot's cockpit. The stick is supported at the bottom by something equivalent to a universal joint, so that the top of the stick can be moved in any direction. The control cables from the elevator are connected to the stick in such a way that pushing the top of the stick forward causes the trailing edge of the elevator to move down and so tends to make the airplane dive. Conversely, pulling the stick back causes the nose of the airplane to rise, so that in either case the airplane rotates in the same direction as the stick. This requires that the cables from the elevator to the stick be crossed; the cable from the lower horn of the elevator is connected to a point on the stick above the pivot, while that from the upper horn is connected to a point below. The cables from the horns on the ailerons are led to the stick in such a way that the moving of the top of the stick to the right causes the trailing edge of the aileron on that side to rise, so that the airplane rolls in the same direction in which the stick is rotated.

In place of the cables several other means are used to transmit the motion of the control stick and rudder pedals to the surfaces. Light steel tubes may act as "push-pull" tubes or, especially to operate ailerons, may be used as "torque" tubes. In the latter case the inner end of the torque tube is often fastened to the control stick by short "push-pull" tubes. On airplanes with quite thick wings it is often practical to conceal the control horns and cables within the fixed surfaces and so reduce the parasite drag.

It is usually more convenient to turn a wheel rather than to push a stick sideways to operate the ailerons; stick controls are found only on trainers, fighters, and some small sport planes. The wheel is mounted on a post or a frame which allows a fore-and-aft motion, so that pulling the wheel toward the pilot or pushing it away moves the elevator up or down. Moving the top of the wheel to the right is equivalent to pushing the stick to the right, hence moves the left aileron down, the right up, and rolls the plane to the right. Figure 62 shows such a control system in a large transport plane.

In some large airplanes, means of assisting the pilot in operating the controls is needed. One scheme is to have the control wheel and pedals open valves allowing oil pressure to move the controls through a hydraulic cylinder. This is called *boost*, and the system must be a

true *servomechanism*, *i.e.*, motion of control surface must be proportional to motion of pilot's controls. In addition, force on pilot's controls should be proportional to movement of surface, and the system must function perfectly all of the time.

FIG. 62. Instrument panel of Lockheed Lodestar. Dual control of wheel type, with rudder pedals. (*Lockheed Aircraft Corporation.*)

It is not possible to describe all the mechanical details of the various control systems, but these are all arranged so that corresponding movements of the controls in different airplanes cause like motions of the airplane. For example, when the pilot pushes the longitudinal control away from him the nose of the airplane drops, regardless of the mechanical details of the system.

CHAPTER VI

THE RECIPROCATING AIRPLANE ENGINE: NOMENCLATURE, ELEMENTARY PRINCIPLES

The engine is truly the heart of the airplane. Like the engines of other vehicles, it furnishes the means for moving from place to place, but, unlike them, it also provides the power necessary for support. When the engine ceases to function, the airplane must immediately start to descend.

The following types of aircraft engine are now in use:

1. The *reciprocating engine.* This type is similar in principle to the gasoline automobile engine and is used to turn a propeller. The propeller creates a driving force, or *thrust,* by blowing air backward from the airplane (see Chap. X).
2. The *turbopropeller engine.* This type, like the reciprocating engine, drives a propeller.
3. The *turbojet engine.* This type creates thrust by blowing a stream of gas backward from the airplane.
4. The *rocket engine.* This type, like the jet engine, creates a thrust by blowing gases rearward.

While these engine types are physically very different, as will appear, they have in common the fact that energy is derived from a chemical reaction. Except in the case of the rocket engine, this reaction occurs between air taken from the atmosphere and a *fuel* such as gasoline or kerosene. In rocket engines all reacting substances, or *propellants,* as they are called, are carried in suitable containers, and if oxygen is used as one of the reacting substances, it is not taken from the atmosphere. In all cases the chemical reaction generates very high temperatures, on account of which fact all these types may be classed as *heat engines.* Furthermore, since *combustion,* or other chemical reaction, takes place inside the engine itself, rather than in an external *furnace* (as in the case of a steam engine), all the engines at present used in aircraft could be classed as *internal-combustion engines.* However, since the rocket engine is basically different from the others in many ways, it is more convenient to consider it separately. Therefore, in the subsequent discussion the term *internal-combustion engine* will not include the rocket engine unless it is specifically mentioned.

Fuel. Except for rocket engines, all types of aircraft engines use petroleum products as fuel. Petroleum as taken from an oil well is a rather thick dark-brown fluid, consisting of various chemical combinations of hydrogen and carbon. It is seldom used in the *crude* state, but is *refined* by various processes to produce gasoline, kerosene, fuel oil, lubricating oil, and various forms of grease, paraffin, asphalt, etc. A few years ago the process of refining consisted chiefly of distilling the crude oil at atmospheric pressure, *gasoline* being the most *volatile*, or easiest-to-evaporate, portion of the distillate. Modern refining of aviation gasoline is a complex process involving not only distillation but also chemical treatment at high temperature and pressure. This changes the structure of the fuel molecules and results in a partly *synthetic*, or artificial, product which is better than that produced by simple distillation. Gasoline is still the most volatile product from the crude oil, *i.e.*, the one that evaporates most easily. The portions that evaporate next are known as kerosene. Next in volatility comes *fuel oil*, which comprises a very large group of oils ranging all the way from *distillate* and *domestic furnace oil*, which are only slightly less volatile than kerosene, to various grades of *diesel oil*, and to the *bunker oil* used under steam boilers, which is relatively thick and *nonvolatile*. The heaviest portions of petroleum are refined into *lubricating oil*, with semisolid products left over, such as *paraffin wax* and *asphalt*. Petroleum is found in abundance in many parts of the world. It can be easily transported by water, rail, or pipe line, and the supply appears to be ample for years to come. It is not surprising, therefore, that petroleum products are universally used as fuel for internal-combustion engines.

Fuels used in rockets will be discussed under that heading (see Table 8 in Chap. IX).

THE RECIPROCATING INTERNAL-COMBUSTION ENGINE

By far the largest number of airplanes now in use are powered by reciprocating engines. In fact, the only airplanes which at present use other engine types are very high speed military and naval airplanes. Practically all reciprocating airplane engines are of the four-cycle, spark-ignition type, which is also the type generally used in passenger automobiles. However, the airplane engine differs considerably from the automobile engine in its structural details.

Elements of the Reciprocating Engine. The essential elements of a four-cycle, reciprocating, spark-ignition internal-combustion engine are shown by Fig. 63. The *cylinder* is a short tube, open at one end,

and closed by the *cylinder head* at the other end. Airplane engines have from 4 to 28 cylinders arranged in various ways, as will appear later. The *piston* is a cup-shaped member, arranged to slide back and forth within the cylinder which fits around it closely. Leakage past the piston is prevented by the *piston rings*, which are carried in grooves in the piston and press tightly against the inner walls of the cylinder on account of their springlike action. The *piston pin* passes through the

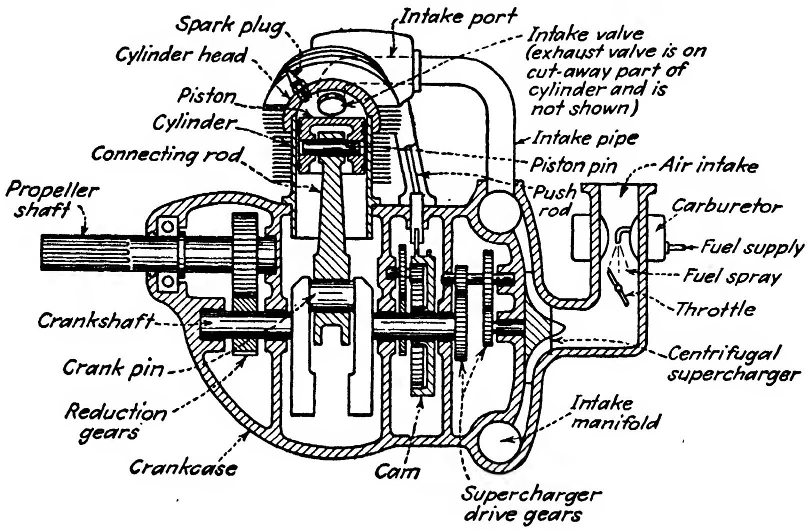


FIG. 63. Principal elements of four-cycle reciprocating airplane engine (diagrammatic), showing one cylinder only.

piston and through the end of the *connecting rod*, the opposite end of which has a hole to receive the *crankpin*. Rotation of the *crankshaft* moves the piston up and down in the cylinder, and pressure on the piston, when applied at the proper time, will rotate the crankshaft. The crankshaft, in turn, drives the *propeller shaft* through an arrangement of gears and shafts called a *reduction gear*, whose purpose is to reduce the propeller speed in relation to the crankshaft speed, in order to ensure high propeller efficiency (see Chap. X). Most small airplane engines omit the reduction gear and mount the propeller on one end of the crankshaft, which projects out of the *crankcase* for this purpose. The crankshaft, reduction gear, valve gear, etc., are enclosed in the *crankcase*, which also supports the cylinders and most of the other parts of the engine. In each cylinder head are mounted the *intake valve* and the *exhaust valve*. Sometimes, there are two or more intake and exhaust valves, but this does not alter the principles of operation.

The valves control the opening from the *intake port* to the cylinder and from the cylinder to the *exhaust port,* respectively. They are operated by a mechanism driven from the crankshaft, which will be described later. The intake port is connected to a passage, called the *intake pipe* or *intake manifold.* Various modifications of these elements are possible, as will appear as our discussion proceeds.

An important element of all large reciprocating aircraft engines is the *supercharger*, which is an air pump for the purpose of supplying air to the inlet manifold at higher than atmospheric pressure. This pump is usually of the *centrifugal* type, as shown in Fig. 63, and is driven by means of gears from the engine crankshaft. It operates on the principle of a centrifugal fan and is capable of delivering air to the manifold at a pressure from two to four times the pressure of the surrounding atmosphere. Only so-called "light-plane" engines are not equipped with superchargers at the present time. Such engines, like automobile engines, operate with about atmospheric density in the inlet manifold when the *throttle* is wide open.

The sizes of supercharger, intake manifold, cylinders, valves, and exhaust port are chosen to accommodate the volume of air which must pass through them per unit time, in order to give the necessary power.

Fuel is introduced into the engine either somewhere in the inlet system or directly into the cylinders. The most usual method is to spray the fuel into the air at the entrance to the supercharger, or at the inlet-manifold entrance in the case of unsupercharged engines. In either of these cases a device called a *carburetor* is used to atomize the fuel and to regulate the flow of fuel so that it will be in proper proportion to the flow of air. This method of introducing the fuel is much more common than any other, and is used on most airplane and automobile engines. Engines using this method of fuel supply are called *carburetor engines.*

In some cases, instead of using a carburetor, the fuel is pumped or *injected* directly into the cylinder through a *fuel-injection nozzle.* Engines using this system are called *fuel-injection engines.* In a few instances injection is into the inlet ports rather than into the cylinders.

The *exhaust valve* is for the purpose of allowing the burned gases to escape after they have been used. They are discharged to the atmosphere from the *exhaust port* through a short *exhaust pipe* or through an exhaust *manifold*, or a *muffler*, though the latter is rare in airplane practice. There is screwed into the cylinder, near the top, one or more *spark plugs* connected by wires to an electric generator called a *magneto.*

The diameter of the inside of the cylinder is called the *bore;* the distance through which the piston moves from one extreme to the other is called the *stroke*, and the area of the top of the piston in square inches multiplied by the length of the stroke in inches multiplied by the number of cylinders is called the *piston displacement* of the engine. The extreme inner position of the piston is called *top center;* and the extreme outer position, *bottom center*. The space in the cylinder above the piston at top center is called the *compression space*, or *combustion chamber;* and its volume, the *compression volume*. The ratio of the volume of the cylinder with the piston at bottom center to the compression volume is called the *compression ratio*.

Control of the power output is obtained by means of the *throttle*, which is a valve located near the *air intake* and usually incorporated in the carburetor. By manipulating this valve, the pilot regulates the air pressure in the inlet manifold, which in turn controls the amount of air and fuel going into the cylinders and thus controls the power of the engine. Reducing the engine power by progressive closing of the throttle is called *throttling* the engine.

ENGINE CYCLES

The sequence of events from the time the fresh air is drawn into the cylinder until the burned gases are discharged is called the *cycle* of the engine. There are several different cycles on which internal-combustion engines may operate, but only those which are of importance to aircraft engines will be described here. Engine cycles are generally classified as *two-stroke* or *four-stroke* cycles, depending upon whether the cycle is completed in two or in four strokes of the piston. Engines using these cycles are called *two-cycle* and *four-cycle* engines, respectively.

Four-stroke Spark-ignition Cycle. Referring to Fig. 64 at *a*, the piston is shown near the top-center position of the *intake* or *suction* stroke. As the crankshaft is revolved by the starter, or by the other cylinders after the engine has started, the intake valve opens and the downward motion of the piston draws fresh air into the cylinder. In the case of carburetor engines, the fuel is already mixed with this air in the form of vapor and fine particles of liquid. In the case of fuel-injection engines, the fuel is introduced later in the cycle. Soon after the piston reaches bottom center, the cylinder is filled and the intake valve is closed. The piston then moves back toward the cylinder head on the *compression* stroke, as shown at *b*. The purpose of the compression stroke is to compress the air or the mixture of air and fuel vapor into a smaller space, thus increasing its pressure and tempera-

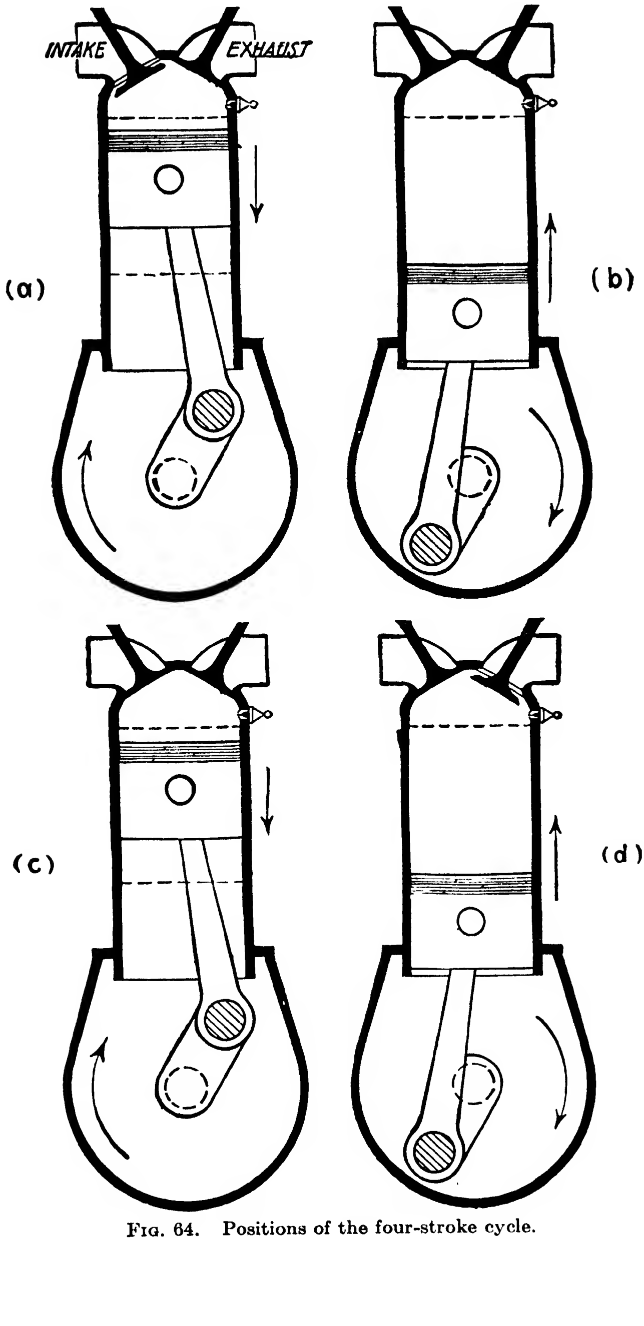


FIG. 64. Positions of the four-stroke cycle.

ture. It has been found that much more power is developed by the engine if the air or mixture is compressed than if it were simply burned at atmospheric pressure. In the case of the carburetor engine, the preparation of the explosive mixture is now complete, and near the top of the compression stroke an electric spark is caused to pass between the points of the spark plug, the mixture is ignited, and the fuel vapor combines with the air very rapidly, in the process of combustion. This rapid burning of the fuel generates a very high temperature and pressure in the cylinder, and the piston is driven down with great force on the *power* stroke, shown at *c*. The work done on the piston during this stroke furnishes energy to turn the crankshaft through all the other strokes, with enough left over to do useful work. Near the end of the power stroke the exhaust valve opens, allowing the burned gases to escape, and as the piston moves toward the cylinder head on the *exhaust* stroke *d*, most of the remaining burned gases are pushed out through the exhaust valve and the cylinder is ready for the inlet stroke again.

It should be noted that there are four distinct strokes of the piston, two toward and two away from the cylinder head, only one of which is a power-producing stroke. The other strokes are used in drawing in and preparing the mixture for combustion or in getting rid of it after it has burned, so that a fresh mixture can take its place.

Four-cycle Fuel-injection Engines with Electric Ignition. Air only is drawn in during the suction stroke. Fuel is sprayed directly into the cylinder during the suction stroke by means of an injection pump and *nozzle* and is ignited by an electric spark as in the carburetor engine. Another method of introducing the fuel is by injection into the inlet port. In this case, the cycle of operations is the same as with a carburetor.

Two-stroke Cycle. Except as an experiment, no airplanes are now using two-stroke-cycle, or *two-cycle*, engines. However, some development work is being done with this type and it may be used in the future.[1]

The two-stroke cycle differs from the four-stroke cycle principally in the process of introducing the fresh air or mixture to the cylinder and of eliminating the exhaust gases. The compression and power strokes take place in the same manner as in the four-stroke cycle. Since the two-cycle engine uses all the in-strokes of the piston for compressing the charge and all the out-strokes for expanding the burned

[1] The Junkers airplane diesel engine, used to a limited extent in Germany, was a two-cycle engine of type *c*, Fig. 65. It is now obsolete (see Ref. E10).

gases and developing power, there are no piston strokes available for drawing in the fresh charge and pushing out the burned gases. In the two-cycle engine, these functions are accomplished by a separate

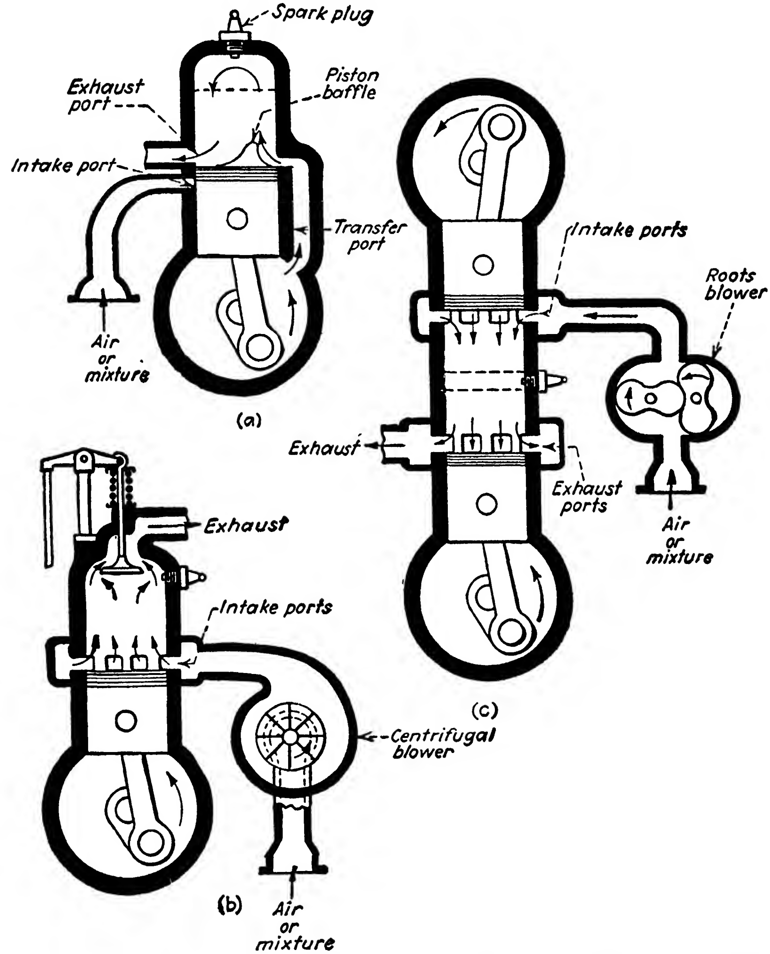


FIG. 65. Two-cycle engine types. (*a*) Crankcase compression. (*b*) Through-scavenging, with centrifugal blower. (*c*) Opposed-piston, with Roots blower.

pump, called a *scavenging pump,* during the "between-strokes" period when the piston is moving slowly near the bottom-center position. Figure 65 shows several different forms of the two-cycle engine. At *a* is shown the simplest type, which has occasionally been used for light airplanes, and is now in general use for small motorboats. The

scavenging pump is formed by the under side of the engine piston, working in an airtight crankcase. Near its bottom-center position, the piston uncovers first the *exhaust port*, allowing most of the exhaust gases to escape, and then the *transfer port*. While both ports are open, the fresh gases from the crankcase, which have been lightly compressed by the downward motion of the piston, force their way into the cylinder and are deflected upward by the *baffle* on the piston top. As the fresh mixture proceeds into the cylinder, it drives ahead of it some of the remaining exhaust gases, although some of these gases mix with the fresh charge and some of the fresh charge may escape through the exhaust port. During the scavenging period the piston has been moving, and the ports are finally closed by the upward motion of the piston, after which the compression and power strokes follow as in the four-stroke cycle.

The pumping action in the crankcase is due to the partial vacuum created therein, when the piston rises. This vacuum draws in air or a fresh mixture as soon as the bottom edge of the piston uncovers the *intake port*. On the downward stroke of the piston this port is covered and the charge in the crankcase is compressed enough so that it flows into the cylinder as soon as the *transfer port* is uncovered. This type of engine has no valves, and is therefore very simple and inexpensive. On the other hand, its output is limited by the limited capacity of the crankcase pump, and there may be excessive mixing of the fresh charge and burned gases, owing to the necessarily curved path of the fresh charge through the cylinder. These difficulties may be overcome in a large measure by the use of a separate scavenging pump and by the use of valves or ports at both ends of the cylinder.

At *b* in Fig. 65 is shown a diagram of an engine with a separate scavenging pump, intake ports in the cylinder, and an exhaust valve in the cylinder head. The scavenging pump may be made as effective as is necessary, and the fresh charge pushes the burned gases straight through the cylinder, with the minimum of mixing of the two. It should be noted that the functions of the valve and ports can be reversed, *i.e.*, intake through the valve and exhaust through the ports, without affecting the principles of operation of the engine.

At *c* of Fig. 65 is shown an *opposed-piston* arrangement, which has ports at both ends of the cylinder and allows the fresh charge to push the exhaust gases straight through the cylinder. It avoids valves, but there are two crankshafts which must be geared together.

Two-stroke Fuel-injection Cycle. While we have assumed a carburetor engine in describing the two-stroke cycle, any aircraft two-

cycle engines which prove successful are more likely to use fuel injection in order to avoid waste of fuel through the exhaust ports during the scavenging process. In such cases, the fresh charge introduced by the scavenging pump consists of air only. The fuel is injected after the ports are closed. Any of the engines shown in Fig. 65 could be used with fuel injection.

Attractive features of the two-cycle engine are the elimination of poppet valves (except in type *b*, Fig. 65) and the fact that with a given number of cylinders, there will be twice as many power strokes per revolution of the crankshaft. The latter fact must not be taken to mean, however, that with two engines of equal size the two-stroke engine will be the more powerful. As a matter of fact, the four-stroke engine, if provided with an air pump (or *supercharger*) corresponding to the scavenging pump required by the two-stroke engine, can usually be made the more powerful of the two. Another difficulty with spark-ignition two-stroke engines is that they may not run reliably or steadily at light load. This latter difficulty must be overcome if they are to be satisfactory for use in airplanes.

The Diesel Cycle. The diesel cycle may be used with either the four-stroke or two-stroke method of operation. This cycle differs from the corresponding cycle with spark ignition only in having a very high compression ratio and having the fuel injected into the cylinder in the form of a spray, just before top center on the compression stroke. The fuel ignites by the heat of compression soon after the injection starts, thus rendering spark ignition unnecessary. Diesel engines have been used to a very limited extent in aircraft, mostly in Germany before the Second World War (see Ref. E10). In spite of the fact that such engines can use a less volatile and therefore a less inflammable fuel than gasoline, they have never been able to displace the gasoline engine for aircraft use, chiefly on account of their greater weight for a given power output.

VALVE GEAR

All four-cycle engines and many two-cycle engines are equipped with valves of some kind. These are usually *poppet valves*, which is the name given to the disc-shaped valve on a *stem*, which opens by being pushed into the cylinder by the *valve gear*.

A typical mechanism for operating poppet valves is shown by Fig. 66. The names of the various parts are given on the diagram. The principal operating member is called a *cam* and consists of a cylindrical, or disc-shaped, member carrying on its circumference a rounded pro-

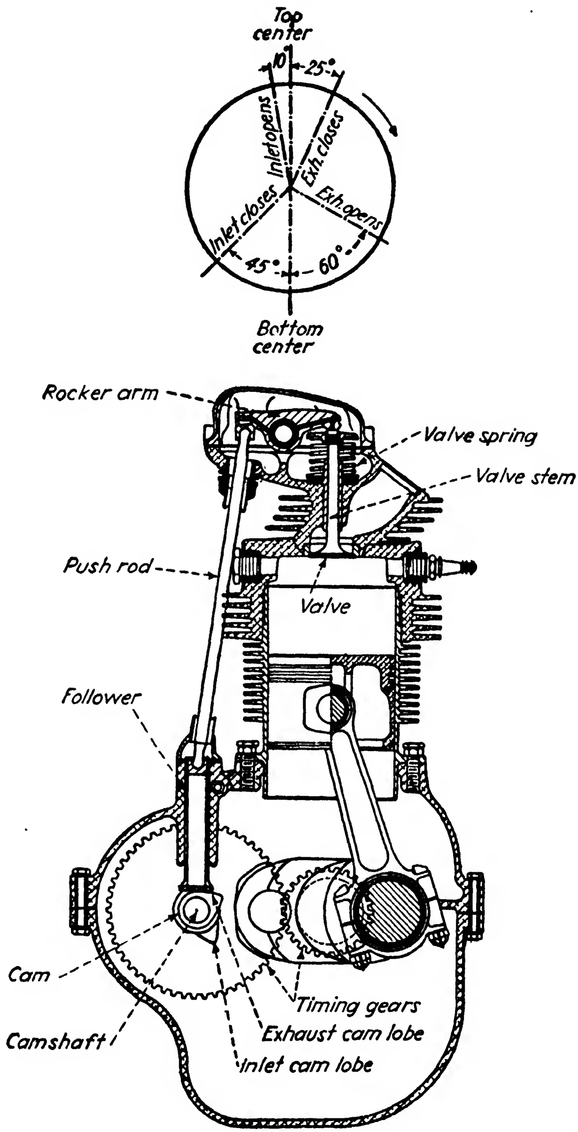


FIG. 66. Valve mechanism and timing diagram, four-cycle engine. Diagram shows exhaust-valve mechanism only. Inlet-valve mechanism is similar, and in the engine illustrated is located behind the exhaust-valve mechanism.

jection, or *lobe.* The cam is mounted on the *camshaft,* which is revolved by means of the *timing gears.* The valve is opened when the lobe of the cam pushes up the *follower,* the motion of which opens the valve. In the arrangement illustrated, the follower motion is transmitted to the valve through a *push rod* and *rocker arm.* As the lobe of the cam leaves the follower, the valve is closed by the *valve spring.* In a four-cycle engine, each valve is required to open once during every two revolutions of the crankshaft, from which it is evident that the camshaft must run at one-half crankshaft speed. For two-cycle

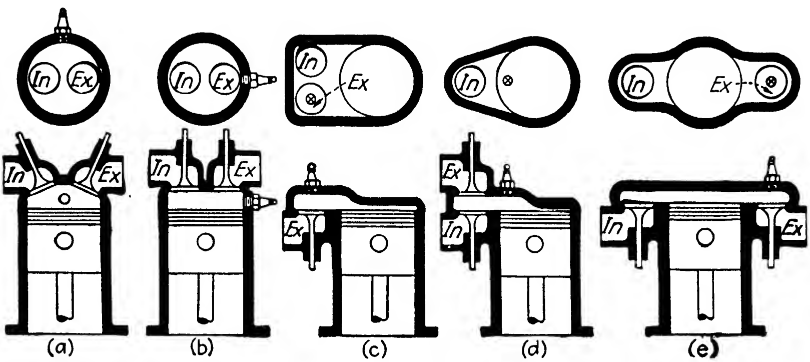


FIG. 67. Cylinder-head and valve arrangements. (*a*) Valves in head, inclined. (*b*) Valves in head, vertical. (*c*) L head. (*d*) F head. (*e*) T head. (All pistons are shown in top-center position. ⊗ in top view indicates spark-plug location.)

engines, the camshaft and crankshaft must run at the same speed. In some engines the cam carries more than one lobe, in which case the speed of the camshaft must be correspondingly reduced. Sometimes the camshaft is carried along the top of the cylinders, and the cams act directly on the rocker arms or valves. This is called an *overhead-camshaft* valve gear.

In order that the valves may function properly, the *timing,* or relation of the opening and closing of the valves to the crank position, must be correct. A typical timing of the valves for a four-cycle engine, measured in degrees of crank rotation with respect to the top- and bottom-center positions of the piston, is given in Fig. 66.

Location of Poppet Valves. Poppet valves may be located in different positions with respect to the cylinder. Figure 67 illustrates various arrangements which have been used in internal-combustion engines: *a* and *b* represent the *overhead-valve* position. This is almost universally used for aircraft engines, for it gives a stronger construction than any other type and a combustion chamber which has less wall

surface to take heat from the gases. It is also easier to cool this type of head, especially with air, since it is of simple shape and has no pockets between the ports and the cylinder. Type *a* is used for most air-cooled engines, since it gives more room between the ports for cooling air, and more room for *cooling fins* on the head. Type *c* has been used on small airplane engines on account of the simple and compact valve-operating mechanism which it allows. Types *d* and *e* are now practically obsolete, especially type *e*, which gives an exceptionally poor shape to the combustion chamber.

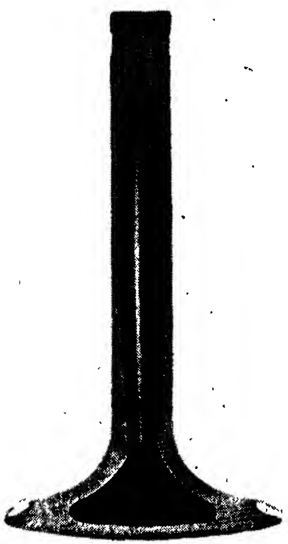


FIG. 68. Section of sodium-cooled exhaust valve. (*Thompson Products, Inc.*)

Valve Temperatures. Poppet valves, being almost entirely surrounded by gases at all times, run at a temperature that is controlled to a considerable extent by the temperature of the gases that pass around them. This gives no difficulty in the case of the intake valve, which is cooled by the fresh incoming charge. Exhaust valves, on the other hand, are subjected to the extremely high temperature of the exhaust gases that pass over them. This causes exhaust valves themselves to run at relatively high temperatures, sometimes even at "red heat." In the early days of airplane engines, exhaust valves would last only a short time, but improvements in material have gradually overcome most of this trouble. Exhaust valves of modern engines are made of special alloy steels which will retain considerable strength and hardness even at very high temperatures. They usually have hollow heads and stems (Fig. 68), which are partly filled with metallic sodium. This becomes liquid at the running temperature of the valve, and, as it "sloshes" back and forth owing to valve motion, it conducts heat from the valve head to the stem, where it can escape to the valve guide.

Sleeve Valves. The sleeve valve (Fig. 69) consists of a thin cylindrical *sleeve* which fits closely in the cylinder and surrounds the piston. In order to prevent leakage at the top of the sleeve, the cylinder head projects into it and is fitted with one or more packing rings similar to those of the piston, called *junk rings.* The sleeve has a combined

rotating and reciprocating motion imparted to it by a small crank which rotates in a plane at right angles to the cylinder axis. It is used on some English aircraft engines (see Figs. 89 and 93).

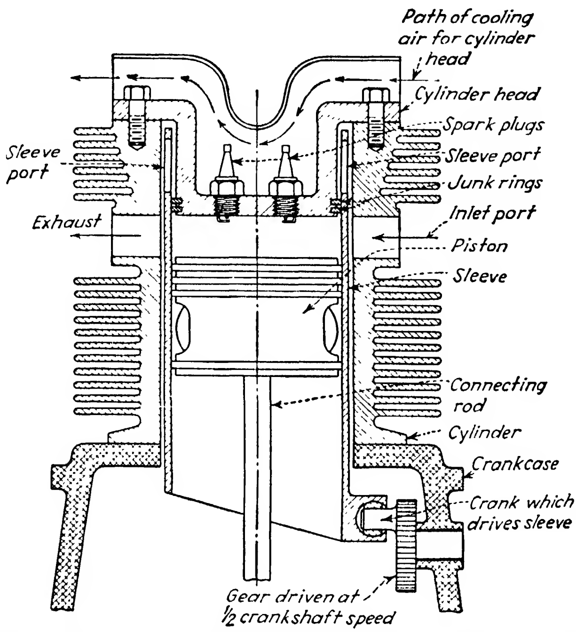


FIG. 69. Sleeve-valve air-cooled cylinder (clearances around sleeve are exaggerated for clarity).

Sleeve and Poppet Valves Compared. The great advantage of the sleeve valve is that it operates at a low temperature, owing to the large surfaces in contact with the cylinder walls. It also gives a very compact and desirable form of combustion chamber. On the other hand, it makes cooling of the piston and cylinder head more difficult.

COOLING

During the process of combustion, the temperature of the gases in the cylinder of any internal-combustion engine becomes extremely high, often in excess of 4500°F. With the gases in the cylinders at such temperatures, it is quite evident that a great deal of heat will be transmitted to the engine parts in contact with the gases and that, unless some provision is made to carry away this heat, the cylinder, piston, and valves will attain very high temperatures. In order to

prevent these parts from becoming too hot, it is necessary to take away the heat as rapidly as it is received from the hot gases. This is the function of the *cooling system.*

Air Cooling. There are two distinct methods of cooling the cylinders of an internal-combustion engine. The first and simpler method is called *air cooling.* Air is blown against the cylinders in such a way and at such a velocity that it will take heat away from the outside of the cylinder and the cylinder head rapidly enough so that cylinder, valves, and piston remain at safe temperatures. The surface of a smooth cylinder does not present sufficient area for this purpose, and in order to be able to cool the cylinder with a reasonable air speed, thin projections, or *fins* (see Figs. 66 and 69), are added to the cylinder over all its outer surface. These provide a much greater total area in contact with the cooling air than in the case of a smooth cylinder. In the airplane engine, the air necessary for cooling is usually supplied by the propeller and by the motion of the airplane through the air. The cylinders, therefore, must be so arranged that air can reach each one in adequate quantities and flow over its entire surface. In order to accomplish this, the cylinders are separate, one from another, with spaces between them. Air passages formed by sheet-metal *baffles* are used to assist in distributing the cooling air over the cylinders (see Figs. 94 and 95).

Liquid Cooling. Another method of cooling is to provide a *water jacket,* or space around the cylinder and cylinder head which can be filled with cooling liquid. This space is kept full during engine operation, and the liquid is circulated through a device known as a *radiator.* The radiator is an assembly of small tubes or flat metal passages through which the liquid is allowed to flow. The outside surface of these passages is exposed to the moving air, and the liquid passing through them is thus cooled. After passing through the radiator, the liquid is circulated back to the engine, where it again receives heat and is sent back to the radiator to be recooled. It is evident that, even with liquid cooling, air is really the cooling medium. In the case of the liquid-cooling system, the liquid simply acts as an intermediate vehicle between the cylinder walls and the air.

Liquid-cooled aircraft engines must be supplied not only with *water jackets* surrounding the cylinders and cylinder heads but also with a pump to circulate the liquid and with the necessary piping to carry the liquid from the pump to the cylinder jackets and from the jackets to the radiator. The pump is usually of the centrifugal type, driven through gearing from the crankshaft. The most widely used cooling

liquid for aircraft is a mixture of water and ethylene glycol. Details of the cooling system are discussed more fully later.

LUBRICATION

In order to avoid excessive friction and excessive wear of bearing surfaces, *lubrication* is necessary. Aircraft engines are lubricated by oil supplied to the bearings under pressure. Pumps driven by the crankshaft are used for this purpose. An oil pump is usually in the form of a pair of spur gears which receive the oil between their teeth and carry it around to the discharge side of the pump. The pressure of the oil, which is usually between 50 and 100 lb per sq in., is regulated by a small spring-loaded *relief* valve. Oil from the pumps is led through suitable passages to the various bearing surfaces. The details of typical lubrication systems are given in Chap. VII in connection with descriptions of particular engines and installations.

ENGINE AUXILIARIES

The Carburetor. The carburetor is the device used by most aircraft engines to introduce fuel into the air which flows into the engine. The carburetor is essentially an automatic device for controlling the fuel-air ratio. It may also, and usually does, contain the throttle valve for controlling inlet air density and hence engine power output.

The ratio of fuel to air supplied to an engine has a profound effect on its performance. This matter is discussed in some detail in Chap. IX. In the case of reciprocating aircraft engines, the required fuel-air ratio depends chiefly on the *load*, or ratio of power output to rated power output of the engine. Typical curves of fuel-air-ratio requirements vs. load are shown in Fig. 70. The purpose of the carburetor is to control the flow of fuel into the engine in such a way as to meet these requirements.

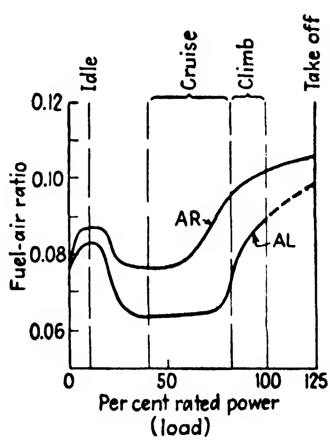


Fig. 70. Fuel-air ratio vs. load for a typical supercharged aircraft engine. AR indicates "automatic rich" setting. AL indicates "automatic lean" setting.

Some of the carburetors now used on large aircraft engines are very elaborate and complex. However, the basic principles by which most carburetors operate can be learned by considering the simpler type

of carburetor such as is used for automobile engines and on engines for light airplanes. Figure 71 shows the basic elements of this type of carburetor. There is a main air passage through which the engine draws its supply of air. Near the middle of this passage is a restriction, or *venturi*, the purpose of which is to increase the velocity of air at the point where the fuel is introduced. Fuel is introduced through the *nozzle* whose outlet is at the smallest diameter of the venturi. In the outlet end of the air passage is the *throttle valve*. The throttle

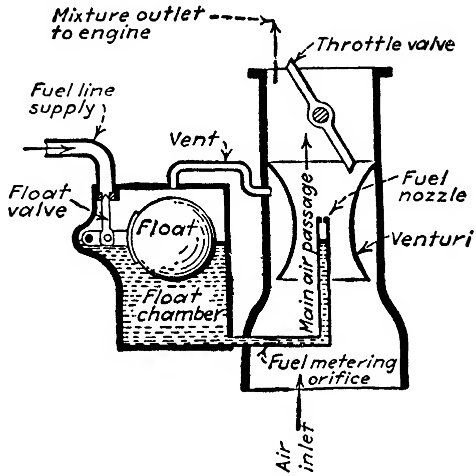


FIG. 71. Carburetor diagram showing main air and fuel passages.

valve shown in the illustration is called a *butterfly* throttle and is the type commonly used. It is simply a disc, mounted on a shaft so that it can be turned in the passage to close it off completely or to allow any desired degree of opening from the carburetor to the engine. The throttle is the main engine control, since it regulates the amount of air and fuel mixture received by the engine. The accelerator pedal of an automobile or the throttle lever in an airplane is connected to the throttle valve. The fuel nozzle receives its supply of fuel from the *float chamber* which carries the *float*. The purpose of the float is to maintain a constant level of gasoline in the float chamber. For this purpose, it is connected to a *float valve* which controls the supply of fuel from the fuel tank. If the float rises above the proper level, it closes the valve, and when the level begins to fall, opens it again. The fuel-supply line from the tank is shown in the figure. The top of the float chamber must be connected, by a small passage or *vent*, to some part of the carburetor which is at the same pressure as the air inlet.

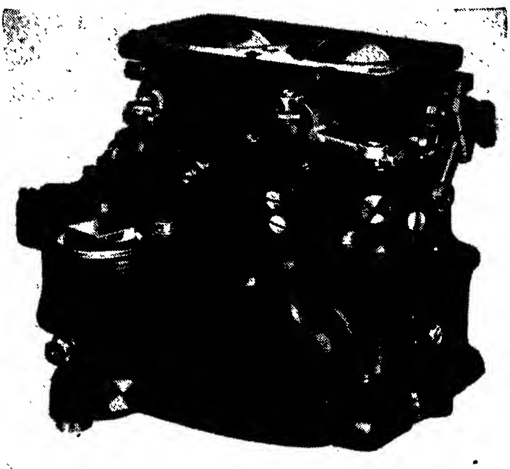
Carburetor Action. The action of the carburetor is as follows: The engine draws air through the venturi past the fuel nozzle, and the suction so created draws gasoline from the nozzle. The fuel leaves the nozzle in the form of a fine spray, which is carried along with the air and mixes with it. A large part of the gasoline actually evaporates into the air during its passage through the intake manifold, but there is usually some gasoline left in the form of liquid when the mixture enters the cylinders. Heat from the cylinder walls, from the piston, and from the exhaust gases remaining in the cylinder evaporates such liquid gasoline, so that most of the fuel is in true vapor form before ignition occurs. One reason that engines sometimes do not start when cold is that there is not enough heat in the engine parts to evaporate enough gasoline to allow combustion to take place.

The simple carburetor elements shown in Fig. 71 can be designed to give the desired fuel-air ratio over the cruising range. Additional parts, not shown in the diagram, are required to secure the proper ratio of fuel to air at *idling* and at low speeds and loads when the flow of air is slow. Other devices are necessary to give the proper mixture ratio for take-off and full-power operation, for starting, and for a sudden *acceleration* or increase in speed of the engine.

The Complete Carburetor. Figure 72 shows in detail the various devices which are commonly used to modify the simple carburetor already described so that it will give the proper mixture ratio for all conditions of engine operation.

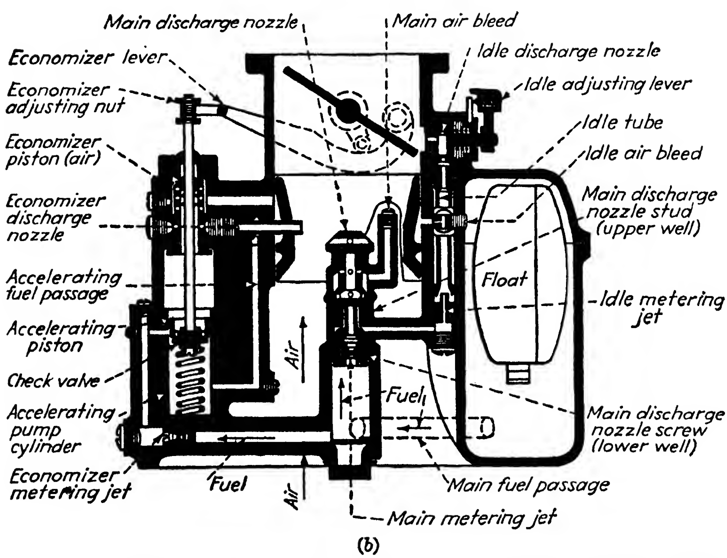
For **starting** when an engine is warm, no special modification of the mixture ratio is necessary. When an engine is cold, however, only the most volatile portions of the fuel will evaporate in the manifold and cylinders. An excess of fuel, in other words a very rich mixture, is then necessary in order that there shall be enough of the very volatile portions of the fuel to evaporate to a combustible mixture. This temporary enrichment necessary for cold starting is accomplished in an automobile by the *choke*, while in airplane engines it is usually supplied by *priming*, *i.e.*, introducing an extra amount of fuel directly into the cylinders by an external pump, which is not a part of the carburetor.

For very light loads and for **idling,** the throttle shown in Fig. 72 is so far closed that the air velocity past the discharge nozzle is practically zero, and no fuel is drawn from the nozzle. To supply fuel for this condition, an auxiliary or *idling nozzle* is provided at the edge of the closed throttle, where the air velocity is sufficiently high, owing to the restricted area, to draw the necessary amount of fuel into the air stream.



(a)

FIG. 72a. Aircraft carburetor with two air and fuel passages supplied from a common float chamber. (*Bendix Products Division of Bendix Aviation Corporation.*)



(b)

FIG. 72b. Cross section of aircraft single carburetor. (*Bendix Products Division of Bendix Aviation Corporation.*)

A condition of operation which usually calls for a change in the mixture ratio is the process of suddenly opening the throttle, called *accelerating*. Much of the fuel which passes through the intake manifold runs along its inside walls in liquid form. When the throttle is suddenly opened, the air and vaporized fuel in the manifold can flow quickly to the cylinders, but it takes more time for the liquid fuel to increase its flow rate. This causes a temporary "leanness" at the cylinders, which must be compensated for by adding more fuel at the carburetor until such time as the liquid fuel on the manifold walls has attained the necessary higher speed. This temporary addition of fuel is usually accomplished by a device in the carburetor, known as an *accelerating pump*. In Fig. 72*b* this appears as a vertical cylindrical passage at the left, which is connected to the float chamber in which gasoline normally stands at the float level. A piston, controlled by the throttle lever through the *economizer* lever, works up and down in this cylinder as the throttle is closed or opened. It will be noted that the piston is drilled with two holes beneath which is a check valve. When the throttle is opened slowly, the check valve remains open and no fuel is pumped. With a quick opening of the throttle, however, the check valve closes and the contents of the cylinder are ejected into the air stream through the *economizer discharge nozzle*. This same result may be achieved with other mechanical arrangements, but the one illustrated shows the general principle of most carburetor accelerating devices.

The main metering jet is chosen so as to give the cruising mixture for the range where this ratio is approximately constant (see Fig. 70). An extra fuel nozzle, sometimes called the *economizer*, is controlled by a valve connected to the throttle shaft in such a way as to open and add the necessary flow of fuel for the higher powers as the throttle approaches the wide-open position. In the carburetor shown in Fig. 72*b*, the piston of the accelerating pump controls the economizer fuel passage so as to open it near full throttle, *i.e.*, at heavy loads.

Mixture Ratio at Altitude. The mixture-ratio requirements of an engine at various altitudes are approximately the same as those at sea level. On the other hand, the carburetor just described will increase the fuel-air ratio with an increase of altitude, unless something is introduced to correct this tendency. Without such correction, the engine would receive an overrich and wasteful mixture at any considerable altitude. All airplane carburetors, therefore, require an adjustment, or *mixture control*, for the purpose of correcting the enrichment tendency. Figure 73 shows two types of mixture control used

on aircraft carburetors. In (1) the enrichment tendency is counteracted by partly closing a needle valve in the main fuel passage. In (2) the suction on the nozzle is reduced by partly closing the air vent of the float chamber and allowing a partial equalization of pressure between the throat of the venturi and the air space in the float chamber, through the small passage X. In airplanes with fixed-pitch propellers, these devices usually are controlled by hand from the pilot's station. The procedure at any given altitude is to reduce the mixture ratio by means of the control until a slight reduction in engine speed is noted. If maximum power is desired, the mixture ratio is increased slightly from this point.

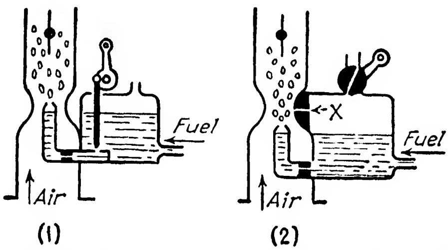


FIG. 73. Two types of carburetor altitude or mixture control. (Float mechanism not shown.)

Since this operation is difficult to carry out with accuracy, and is impossible when a constant-speed propeller is used, automatic operation of the mixture control is provided for all large aircraft engines. In these devices a sealed metal bellows containing a gas is arranged to operate the mixture control valve. A change in atmospheric pressure or temperature causes the bellows to expand or contract and moves the valve to the proper position. Even with automatic mixture control, however, a degree of manual control is provided. Because low fuel-air ratios even in the cruising range may sometimes cause detonation or difficulties with cooling, the pilot is provided with a lever which, when set to "automatic rich," keeps the fuel-air ratio above about 0.08 at all times (see Fig. 70). This setting is used as a matter of precaution during take-off, climb, and landing operations. For cruising, the control is set to "automatic lean," which gives fuel-air ratios as indicated by the lower curve of Fig. 70.

Most **aircraft carburetors** operate on the general principles already described, but their arrangement and mechanical detail vary considerably. Aircraft carburetors are designed to be as light and compact as possible, and to this end several carburetors are often combined in one casting. The carburetor shown in Fig. 72*a*, for instance, is in

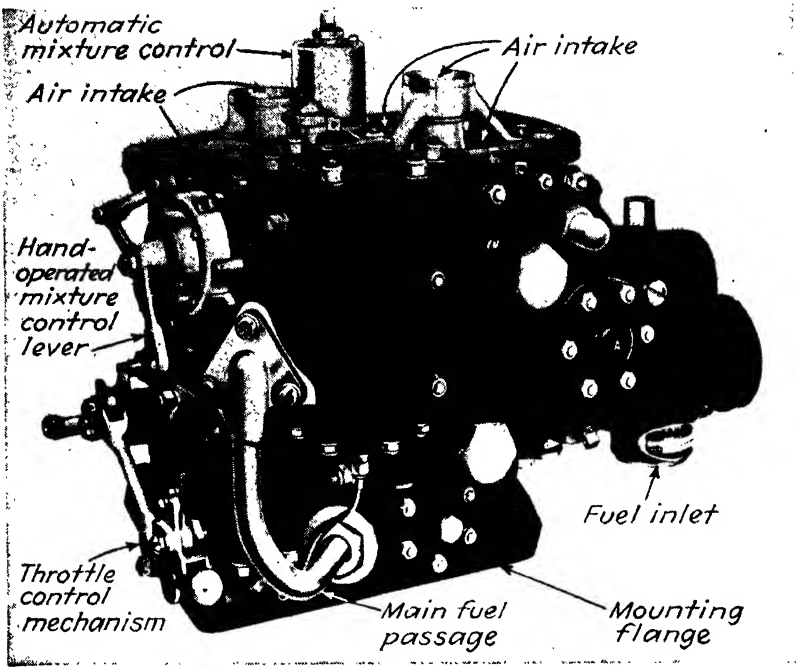
reality two carburetors combined in one casting with a common float chamber. This saves considerable weight and complication over two separate carburetors and allows the two throttles to be mounted on a single shaft, controlled by a single lever. The illustrations of complete engines show the location of carburetors on the various engine types.

Downdraft carburetors are carburetors in which the air and fuel flow downward into the inlet system. In many cases, this affords a more convenient arrangement on the engine, but the principles of operation are exactly the same as in the updraft carburetor. Most carburetors for large engines are now of the downdraft type.

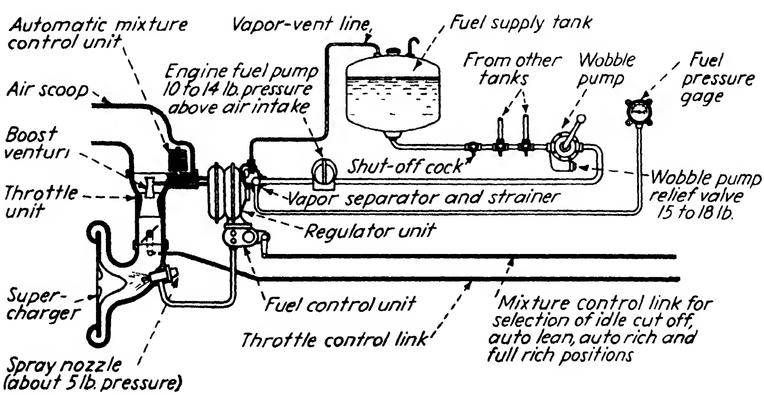
Distribution. The mixture of fuel and air is *distributed* to the various cylinders supplied by one carburetor by means of the intake manifold. This manifold consists of a branched pipe or passage which connects the carburetor with the several intake ports. The manifold must be so designed that it will convey, as nearly as possible, the same amount of air and fuel to each cylinder. When this is accomplished, the *distribution* is said to be good. It is relatively easy to distribute equal amounts of air, and if most of the fuel is in vapor form, the air will carry with it nearly equal amounts of fuel to the various cylinders. In cold weather, when there is much liquid fuel present in the manifold, equal distribution of this fuel is very difficult, as it tends to adhere to the walls of the manifold and flow to certain cylinders more than to others. This difficulty is overcome by heating the inlet air by means of the exhaust gases, so that most of the fuel is evaporated in the manifold. Superchargers heat the inlet air considerably, and engines so equipped do not usually require heating of the inlet air except to prevent ice formation.

Injection carburetors are used for injection of fuel at the manifold entrance or into the air inlet of the supercharger. As in the ordinary carburetor, this type uses the pressure difference caused by airflow through a venturi in the main air stream to control the fuel-air ratio. By means of a system of flexible diaphragms, this pressure difference operates a regulating valve which controls the rate of flow of fuel from a mechanically driven fuel pump to the discharge nozzle. The distinguishing feature of the injection carburetor is that the venturi suction is used for control purposes only; whereas, in the conventional carburetor, it also causes the fuel to flow from the nozzle. Figure 74 shows a modern injection carburetor (see also Ref. E2).

Intake-port Injection. For injection into the inlet ports, a pump delivers a fairly high pressure intermittent spray of fuel through a nozzle directed usually at the inlet valve and timed so as to occur



(a)



(b)

Fig. 74. Injection carburetor. (a) External view. (b) Diagram of supply and control system. (*Bendix Products Division of Bendix Aviation Corporation.*)

during the suction stroke. Pumps similar to diesel injection pumps are generally used. A separate pump plunger for each cylinder may be used, or a single plunger may deliver to two or more cylinders in turn through a timed distributor valve. In a system of this type, used on some light-plane engines, a throttle valve in the fuel line leading to the pump is connected to the air throttle. Apparently this gives sufficiently good control of the fuel-air ratio for this type of engine.

Cylinder Injection for Spark-ignition Engines. An injection valve is located in each cylinder head and is supplied with an intermittent spray, timed to occur during the intake stroke. High injection pressures, as in diesel engines, are usually used. The pumps are quite similar to diesel-engine pumps (see Ref. E8) and usually have one pump cylinder to supply each engine cylinder. Control of the fuel-air ratio is usually accomplished by means of a system responding to the airflow, as in an injection carburetor.

All German combat-type engines used in the Second World War employed cylinder injection. A similar system is now used on several American engines. A basic advantage of the cylinder injection system is that there is never a combustible mixture in the supercharger or inlet manifold and therefore explosions (backfires) and fires in these parts are impossible. Furthermore, *distribution* of fuel to the various cylinders is generally better with the injection system than with the carburetor-manifold system. On the other hand, such a system is considerably more expensive and complicated than even the injection carburetor, and its general adoption, except in Germany, has been quite slow.

Speed-density Mixture Control

The carburetors previously described use the pressure difference caused by airflow through a venturi to control fuel flow. Another method is to use the engine speed and inlet density as the controlling variables.

If a four-cycle engine fills its piston displacement, during each suction stroke, with air at inlet density, the weight of air, M_a, taken in per minute will be

$$M_a = \frac{N}{2} \frac{D}{1{,}728} d_i \tag{1}$$

where N = revolutions per minute
D = piston displacement, cu in.
d_i = air density in the inlet manifold, *i.e.*, the *inlet air density*, lb per cu ft

In actual practice, an aircraft engine takes in about 90 per cent of the air quantity indicated by Eq. (1) when the inlet pressure equals the exhaust pressure. When the exhaust pressure exceeds the inlet pressure, as in a throttled engine, airflow is reduced below this amount, and when the exhaust pressure is less than the inlet pressure, as with supercharging, the opposite is true. Under these circumstances it is evident that airflow through a given engine is determined by crankshaft speed, inlet density, and the ratio of exhaust absolute pressure to inlet absolute pressure. These variables can be used to operate an automatic control system which will supply fuel in such a way as to meet the requirements indicated by Fig. 70. A system of this kind is called a *speed-density mixture control.*

The design and operation of such control systems is too complicated to describe here, but is well covered in Ref. E8. The principal German aircraft engines used in the Second World War were equipped with this type of control. It is particularly well suited for use with cylinder injection systems, which these engines used, as previously mentioned.

Ignition Systems

The basic element of an airplane engine ignition system is a small electric generator called a *magneto.* The principles on which the magneto operates are shown diagrammatically in Fig. 75.

On a shaft rotated at suitable speed by the engine is mounted a permanent magnet. The *poles* of this magnet rotate between the ends of a U-shaped *core* made of iron. Around part of the core is wound a *primary coil* consisting of relatively few turns of heavy insulated wire, and on top of the primary coil is wound the *secondary* coil consisting of many hundreds of turns of fine insulated wire. One end of the primary coil is connected to *ground, i.e.,* to the metal frame of the magneto, which in turn is electrically in contact with the engine crankcase. The other end of the primary coil is also connected to ground, but in this case through a switch, or *breaker,* which is operated by a *cam* on the magneto shaft.

One end of the secondary coil is connected to ground and the other to the *distributor arm,* which is an insulated metal arm rotated at half crankshaft speed either by the magneto shaft or by some other convenient shaft driven by the engine. As the distributor arm rotates, its outer end passes close to insulated contacts, each of which is connected to a *spark plug* through a *high-tension* wire.

In operation, as the magneto shaft rotates, the magnetism of the core is alternately changed in direction as the north and south poles

of the magnet move around. This change in magnetic *flux* generates an electric current in the primary coil. This current is at a maximum at the point where the direction of the flux reverses. At this point the breaker, which is normally closed, suddenly opens, and the current flow in the primary coil ceases abruptly. This sudden change in current flow in the primary coil generates a high voltage in the secondary coil. This voltage is transmitted through the distributor arm to one of the *spark plugs*, where it causes a spark to jump across the *points*

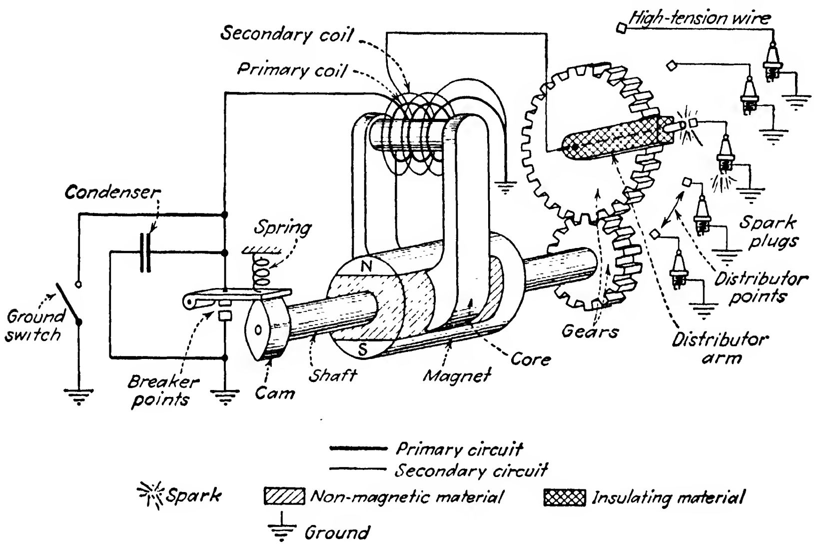


FIG. 75. Diagram of magneto.

of the plug to ground, *i.e.*, to the metal of the engine. This operation is repeated each time the flux in the core changes in direction. With the two-pole magnet shown in Fig. 75, this would occur twice in each revolution of the magnet. Sometimes four-pole or six-pole magnets are used, in which case four or six sparks per revolution would be generated.

In order to stop the engine, the *ground switch* shown in Fig. 75 is closed, thus preventing the breaker from functioning and stopping the flow of current through the high-tension system.

In order that the breaker may function properly, it must be connected with a *condenser* as shown in the figure.

Dual Ignition. The modern ignition system for the aircraft engine has been developed to a very high stage of reliability, but it is still considered advisable to carry two separate ignition systems, each

firing one of the two spark plugs in each cylinder. This objective may be accomplished by mounting on the engine two separate magnetos or a *double magneto* (Fig. 87), which is virtually two separate magnetos in one housing, having the drive shaft, armature, and magnet in common for both units. The double magneto uses two separate distributors, driven independently by the engine.

Spark Plug. The function of the spark plug is to furnish two metal points inside the combustion chamber, one of which is electrically insulated from the cylinder and is furnished with an outside connection, so that when a suitable high-tension current is supplied to the connection, a spark will jump from one point to the other. The spark plug is made as a separate unit so that it can be easily removed from the cylinder for cleaning, repair, or replacement.

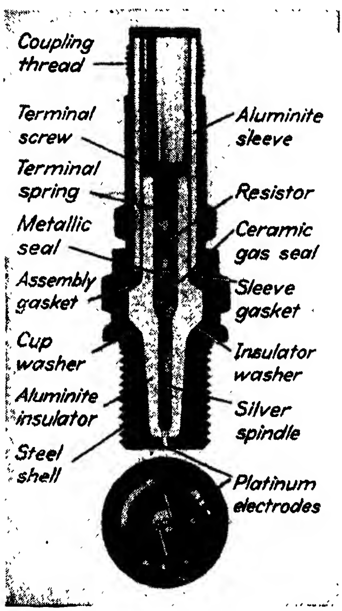


FIG. 76. Aircraft spark plug.

Aircraft Spark Plugs. A cross section of a typical airplane-engine spark plug is shown in Fig. 76. It consists essentially of an outer steel *shell* which contains an *insulator* made of a special ceramic material, in this case called *aluminite*. Through the center of the insulator passes the *spindle*, in this case made of silver, which carries the high-tension current from the magneto to the center *electrode*, or sparking point. Silver is used for the spindle in order to obtain maximum heat conductivity from the center electrode, so as to keep the latter as cool as possible. A *resistor* is used in this particular spark plug for the purpose of reducing the rate of erosion or burning away of the electrodes. The electrodes, or sparking points, are made of platinum, which in itself has a very high resistance to erosion and chemical attack from the products of combustion. The high-tension *lead* from the ignition system fits into the open upper end of the plug.

The entire ignition system must be *shielded* to prevent interference with radio reception. Shielding consists of covering all parts of the system, including the wires, with metal which is grounded to the engine. The spark plug illustrated is shielded by its own steel shell.

The spark plug of Fig. 76 is of the rather elaborate and very expensive type used on large military and transport engines. Light-plane engines use simpler plugs more like those used for automobile engines. Such plugs are satisfactory in the absence of supercharging and high-altitude operation.

Superchargers

In the discussion of engine performance in Chap. IX, it is shown that the power of a given engine, operating at a given speed, is nearly proportional to the air density in the inlet manifold. The object of a

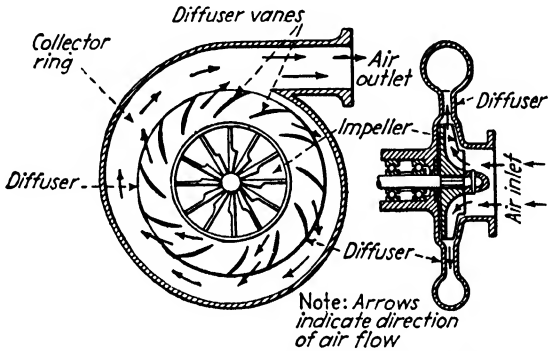


Fig. 77. Diagram of centrifugal supercharger.

supercharger is to increase the inlet air density above that of the atmosphere in order to secure a higher power from the engine than could be obtained with atmospheric density in the inlet manifold. By means of superchargers, reciprocating engines are able to give more than twice the power at sea level, and four or five times the power at high altitudes, than could be obtained without supercharging. Since a supercharger adds very little weight to an engine, the saving in weight per horsepower by its use is tremendous. All reciprocating engines above the light-plane class, *i.e.*, above about 300 hp, are now equipped with superchargers.

In discussing superchargers the term *pressure ratio* is convenient. Pressure ratio is defined as the ratio between the outlet and the inlet pressure of the supercharger, both measured in absolute units. For example, a supercharger with a pressure ratio of 2 will give an outlet pressure of $2 \times 30 = 60$ in. of mercury when the atmospheric absolute pressure is 30 in.

The Centrifugal Supercharger. This is the only type of supercharger in general use in aircraft engines. As shown in Fig. 77, it

consists of a bladed wheel, or *impeller*, which rotates within a circular casing. Air, or a mixture of air and fuel, enters near the center of the wheel. The rotation of the wheel is imparted to the air, which is thrown outward by centrifugal force into a narrow annular space fitted with stationary curved vanes and called the *diffuser*. As the air passes through the wheel and the diffuser, its pressure increases owing to centrifugal force and to the conversion of kinetic energy into pressure energy in the diffuser. The pressure thus built up is nearly proportional to the square of the wheel velocity. From the diffuser, the compressed air or mixture is discharged into the circular *collector ring*, from which it is delivered, through one or more inlet pipes, to the cylinders.

The normal speeds for this type of supercharger range from 10,000 to 35,000 rpm. The centrifugal stresses in the blower wheel are very high at such speeds, and it must be carefully made of the very best material. Forged aluminum alloy is generally used for this purpose. The casing is made of cast aluminum or magnesium and the shaft and gears of alloy steel of very great strength. Bearings may be either plain bronze bushings or ball or roller bearings.

Supercharger Drives. Most modern supercharged airplane engines contain at least one supercharger driven by gears from the crankshaft. This supercharger is built into the engine structure, of which it forms a permanent part. Gear-driven superchargers generally use spur gears, the first gear of the group usually being connected to the rear end of the crankshaft. A single pair of gears may be used, but where it is desired to have the blower shaft on the same axis as the crankshaft, a train of four spur gears is necessary. Such an arrangement is shown in Fig. 63.

The simplest arrangement in use consists of a *single-stage, single-speed* supercharger. This designation means that there is only one supercharger impeller and that it runs at a fixed speed in relation to the crankshaft. Such superchargers are generally designed for *critical altitudes* not over 10,000 ft. The critical altitude is the maximum altitude at which rated sea-level power can be maintained by the supercharger.

The use of the single-speed arrangement involves some wasted power when the engine is not being operated at full throttle. In order to reduce the power lost at low altitudes when the engine is throttled, a *two-speed* supercharger drive may be used. This designation means that the pilot has a choice of two gear ratios between supercharger and crankshaft. With such an arrangement the low gear ratio is used at

low altitudes and less power is wasted. In low gear ratio the critical altitude is usually 3,000 to 5,000 ft. In the high ratio, the critical altitude may be from 15,000 to 20,000 ft.

Engines designed for very high altitude work may be equipped with a *two-stage* supercharger. Such a supercharger consists essentially of two superchargers in series. In this case the pressure ratio of the combination is equal to the product of the pressure ratios of the two separate superchargers. For example, if each supercharger in the combination has a pressure ratio of 2, the pressure ratio of the combination will be 4. Two-stage superchargers are invariably equipped with two or more gear ratios, and sometimes each stage is so equipped, in order to secure most efficient operation at various altitudes and with various loads on the engine.

Exhaust-driven Superchargers. In the case of engines equipped with single-stage superchargers, a second stage of supercharging may be provided by the addition of an *exhaust-driven* supercharger. Many United States aircraft used in the Second World War were so equipped. (Examples were the P-47, B-17, B-24, and B-29 airplanes.)[1]

Figure 78 is a diagram showing the general arrangement of an exhaust-driven, or *turbosupercharger*. In this case the supercharger is driven by a small *turbine*, similar to a single-stage steam turbine, but using exhaust gases from the engine as its source of energy. In order to drive the turbine, the pressure in the exhaust system must be considerably higher than atmospheric. The exhaust pressure is regulated, either automatically or by the pilot, by means of the *waste gate* shown in the figure. The increase in exhaust pressure above atmospheric involves, of course, some sacrifice in engine power, though usually less than would be required to drive the supercharger by gears.

Referring to Fig. 78, the *turbine wheel* is mounted on the same shaft as the supercharger impeller. The exhaust gases from the engine pass through suitable piping to a series of *nozzles*, which direct the gases against the turbine *buckets* or blades and cause the turbine *wheel* to rotate. Since the exhaust gases passing from the engine to the turbine are very hot, the passages from the engine exhaust ports to the turbine nozzles, and the wheel and blades of the turbine, must be made of stainless steels, which are extremely resistant to corrosion or distortion at high temperature. Aluminum alloys cannot be used where they are swept by the hot exhaust gases of an engine. The great advantage of the turbine drive, aside from the entire absence of gears, is that it

[1] Recently a large airplane engine whose only supercharger is exhaust-driven has been placed in production.

permits the speed of the supercharger to be regulated more or less independently of engine speed. Another advantage, of no small importance, is that the turbosupercharger can be added as a separate auxiliary, to almost any engine. Its great disadvantage is the presence of bulky exhaust pipes and passages which run at high temperatures. This type of supercharger drive is economical of engine power at very high altitudes, since here the sacrifice in power necessary on account

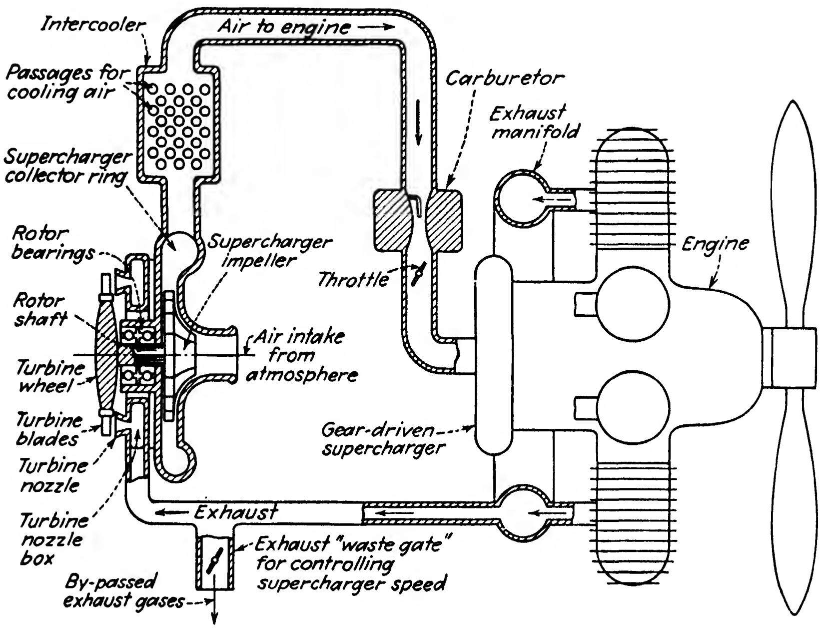


FIG. 78. Diagram of exhaust-turbine-driven centrifugal supercharger.

of high exhaust pressure is generally not as great as the power which would be required to gear-drive the same supercharger.

Intercoolers and Aftercoolers. Compressing air in a supercharger raises the inlet temperature considerably. High inlet temperatures are very undesirable because they promote detonation and reduce critical altitudes. When two stages of supercharging are used, the inlet temperature will be excessive unless some cooling of the inlet air is introduced.

The most effective place for the cooler is between the supercharging system and the inlet manifold. Coolers so located are called *aftercoolers.* In many cases it is inconvenient to install an aftercooler, but feasible to install a cooler between the first and second stages of

the supercharging system as shown in Fig. 78. In this location the cooler is called an *intercooler*.

Intercoolers and aftercoolers are much alike in construction, being made of banks of thin tubes arranged so that the engine air flows through them and air from the atmosphere flows outside of them, or vice versa. Sometimes liquid-cooled engines use liquid-cooled aftercoolers, in which case cooling liquid flows around the tubes and in its turn must be cooled in a radiator, which is cooled by atmospheric air. Figure 92 shows such an aftercooler. The performance of an intercooler or aftercooler is judged by its *effectiveness*, which is the ratio of temperature drop of the engine air to the maximum possible temperature drop, which would be down to atmospheric temperature.

CHAPTER VII

THE RECIPROCATING AIRPLANE ENGINE: ENGINE CONSTRUCTION, TYPICAL ENGINES, ENGINE INSTALLATION

ENGINE CONSTRUCTION

Materials. The materials used in the construction of airplane engines consist largely of aluminum and magnesium alloys and special alloy steels. In general, the crankshaft, camshaft, connecting rods, auxiliary shafts, gears, valves, valve-gear parts, and linings of the cylinders arė made of alloy steel, while the crankcase, cylinder heads and pistons are made of aluminum alloys. Sometimes, however, crankcases are made of steel. The steel parts are generally forged, *i.e.*, formed by hammering between metal dies, after which they are machined all over. Aluminum and magnesium alloys may be forged or *cast*, *i.e.*, made by pouring the molten metal into molds where it cools and hardens in the shape of the mold. Crankcases and cylinder heads and pistons are often made of aluminum forgings. Pumps, carburetors, etc., are usually made of aluminum or magnesium castings, with bronze or steel moving parts. Bolts and nuts are of the best allloy steel, machined all over. Piston rings are of cast iron. Where ball or roller bearings are used, these are made of special alloy steel with a very hard surface. Plain bearings for steel shafts are made of bronze except for the crankshaft and crankpin bearings, which are usually of alloys developed especially for this purpose. Important among these are copper-lead mixtures and silver with a thin lead coating.

Cylinder Construction. The cylinder construction generally used for air-cooled engines (Fig. 79) consists of a steel cylindrical portion, or *barrel*, in which the piston slides. Steel is necessary for the cylinder barrel, for if aluminum were used, the piston and piston rings would wear the cylinder too rapidly. The barrel is covered on the outside with aluminum cooling fins. These may be part of an aluminum jacket shrunk over the barrel, or may be of aluminum sheet fastened to the barrel by a special process (see Ref. E11). In small engines the barrel fins are usually of steel machined, together with the barrel itself, from a single piece.

The cylinder head, inlet and exhaust ports, and rocker-arm housings and their cooling fins are made from a single piece of aluminum, screwed and shrunk on the outer end of the barrel. For the larger engines the cylinder head is made from an aluminum *forging* machined all over, including the fins. For the smaller engines the cylinder head

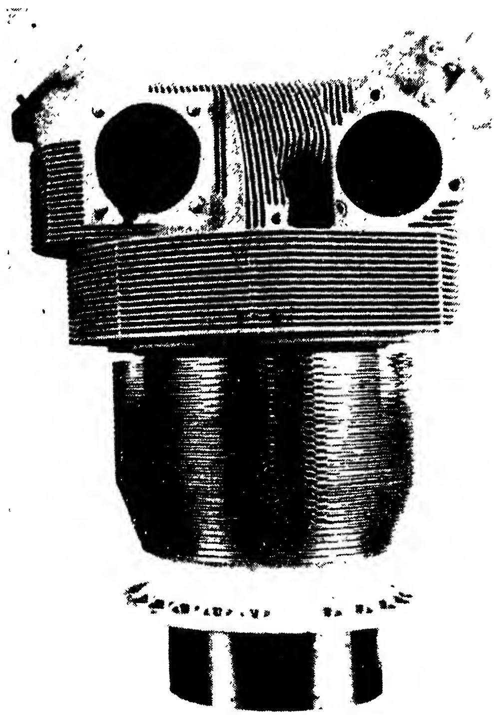


FIG. 79. Modern aircooled cylinder. Head is made from an aluminum forging, machined all over, including the fins. Barrel is a steel forging with sheet-aluminum fins attached by a special rolling process. (*Wright Aeronautical Corporation.*)

is cast in a sand or metal mold. Since aluminum is not hard enough to serve as a bearing surface, steel or bronze valve seats and bronze *valve guides* are used.

In liquid-cooled engines, steel barrels and cast-aluminum heads are also used, but the details of construction are quite different from those of the air-cooled cylinder. In most cases, the cylinder heads and water jackets are cast en bloc, *i.e.*, a single piece for each line of cylinders. The steel barrels are fastened into the *block* by various methods. The whole block assembly is fastened to the crankcase by bolts, which in

some cases extend from the top of the cylinder head to the crankcase structure.

Gear Details. Propeller reduction gears may be divided into two

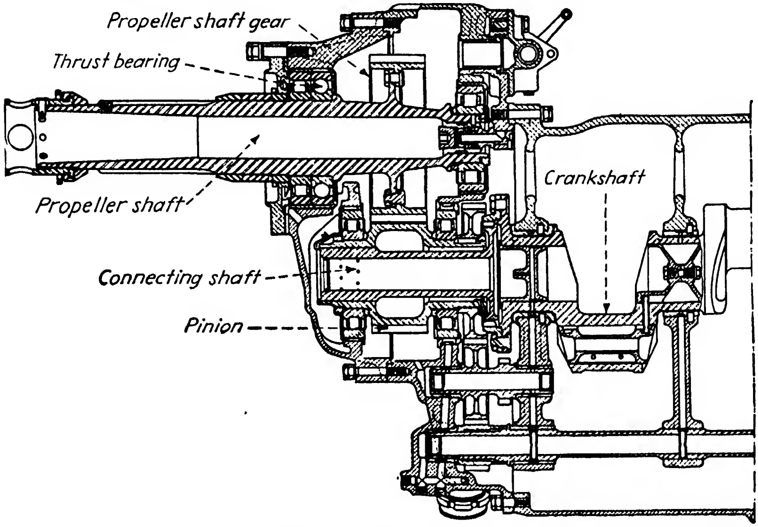


FIG. 80. Spur-type propeller-reduction gear. (*Ranger Aircraft Engines Division of Fairchild Engine and Aircraft Corporation.*)

classes—*spur* and *planetary*. The spur type consists of two gear wheels with straight teeth—a small gear, called a *pinion*, driven by the crankshaft and a larger one mounted on the propeller shaft. Figure 80

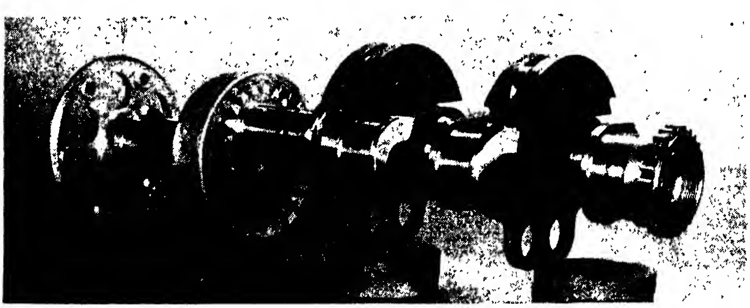


FIG. 81. Crankshaft of a four-cylinder opposed engine, showing internal spur reduction gear and vibration-absorbing counterweights. (*Lycoming Division of Avco Manufacturing Corporation.*)

illustrates a gear of this type. The propeller shaft is carried on roller bearings, with a ball bearing to take the thrust of the propeller.

Another type of spur gear is illustrated in Fig. 81. This is called

an *internal* spur gear, because one of the gear wheels has its teeth cut on the inside of its rim.

The second type of propeller reduction gear is called a planetary gear because it contains several small gear wheels, or *pinions*, which

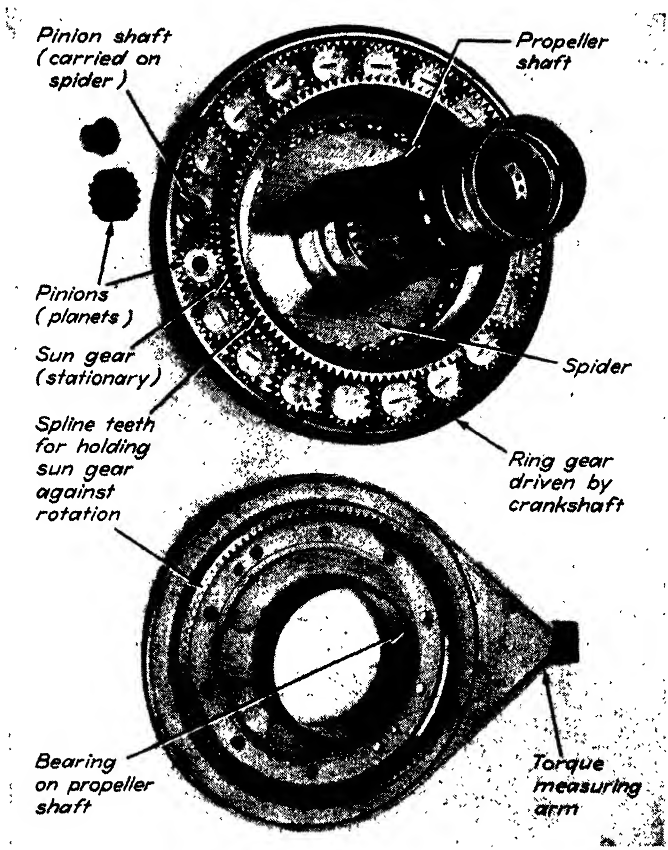


FIG. 82. Planetary propeller-reduction gear. (*Wright Aeronautical Corporation.*)

revolve about their axes and also travel in a circle—a motion similar to that of the planets around the sun. The gear wheels of planetary gears may be of either the spur (straight-tooth) or the *bevel* type, in which the gear wheels are of conical form, like the rear-axle gears in an automobile. Figure 82 shows a planetary gear of the spur type. The crankshaft drives a large internal gear wheel, which drives the pinions or *planets*. These mesh with a spur gear, which is held stationary in the crankcase. The propeller shaft is driven by the *spider*, or frame-

work on which the planet gears are mounted. This causes the propeller shaft to run at considerably less than the speed of the crankshaft, the exact ratio depending upon the relative number of teeth in the gears. Such a gear is used where the propeller shaft must be on the same center line as the crankshaft, as in radial engines.

Types of Engines

Airplane engines are usually classified by the arrangement of their cylinders with respect to the crankshaft. The various common types, according to this method of classification, are as follows:

Vertical Engine. An engine having its cylinders arranged vertically above or below the crankshaft, in a single row.

V Engine. An engine having its cylinders arranged in two rows, in the form of the letter V, both rows of cylinders being connected to the same crankshaft (Fig. 92).

Opposed Engine. An engine having cylinders arranged in two rows on opposite sides of the crankshaft. The cylinders may be horizontal (Fig. 83) or vertical.

H Engine. An engine having two parallel crankshafts, each of which serves two rows of opposed cylinders. The two opposed engines thus formed lie parallel to each other (Fig. 93).

Inverted Engine. An engine of the vertical or V type having its cylinders hung below the crankshaft.

Radial Engine. An engine having cylinders arranged radially, *i.e.*, like the spokes of a wheel, around a common crankshaft (Fig. 84). Radial engines may be made with more than one "wheel" of cylinders behind another (Figs. 87 to 91). These are called "two-row," "three-row" or "four-row" radials as the case may be.

Number of Cylinders

The number of cylinders depends somewhat upon the type but principally upon the size of the engine. For very small engines, as few as two or three cylinders may be used, but in the case of medium and large sizes, a greater number of cylinders is necessary in order to avoid severe vibration. Engine vibration comes from two sources, one of which is the succeeding impulses from the various cylinders. The fewer the cylinders and the larger they are, the greater will be the vibration from this source. In present practice, few airplane engines have less than four cylinders. Four-cylinder engines are usually built for less than 150 hp, and five-cylinder engines do not exceed 250 hp. A

general idea of the relation between engine size and the number of cylinders may be gained from Table 4 at the end of this chapter.

Cylinder Size

Another factor which controls the number of cylinders used for an engine of a given capacity is the maximum practicable cylinder size. If cylinders are made too large, difficulties in cooling the cylinder head, pistons, valves, etc., are likely to be encountered, especially with air cooling. Most airplane engines have cylinders of less than 6½-in. bore and 7-in. stroke.

Maximum Engine Size. The total power which an engine can develop evidently equals the maximum power of one cylinder multiplied by the number of cylinders. In addition, there are limitations on cylinder size, and so on power per cylinder. There is also a practical limit on the number of cylinders that can be employed with the various cylinder arrangements. In the single-row radial engine, for example, nine cylinders is the largest number giving a reasonable relationship among the principal dimensions such as stroke, connecting-rod length, crankcase diameter, and over-all engine diameter. In the same way, 18 cylinders is the maximum practicable number for the usual type of double-row radial engine. For larger numbers of cylinders, the H arrangement and the multirow radial are most common.

One of the important limitations on the design of air-cooled engines is the necessity of providing considerable space for cooling fins between adjacent cylinders. In liquid-cooled engines, on the other hand, the space for liquid circulation may be small (¼ in. or less) where cylinders are placed in line; therefore, the liquid-cooled engine is considerably shorter than the corresponding air-cooled engine. Thus, the in-line cylinder arrangements, such as the V and H types, are more widely used for liquid-cooled than for air-cooled engines.

Engine Balance

Some engine vibration is due to the inertia forces set up by the reciprocating motion of the connecting rods and pistons. With certain cylinder arrangements, the inertia forces in the various cylinders offset each other and the engine is said to have inherent *mechanical balance.* In general, four-cylinder engines cause considerable vibration due to inertia forces and torques, while engines with six cylinders in line, or multiples thereof, are very well balanced. Radial engines of five cylinders or more can be very well balanced by means of proper *counterweights* attached to the crankshaft plus geared counterweights operating

at twice crankshaft speed. Without the latter counterweights, single-row and double-row radials are likely to give more vibration than engines of 12 cylinders or more, and of equal power.

In single-row four-cycle radial engines, where the cylinders operate on a single crank, it is necessary to have the power strokes follow the crank around the engine, skipping every other cylinder, the alternate cylinders ending their exhaust strokes as the crank comes around and firing on the next revolution of the crank. In order to secure even firing impulses in this type of engine, there must be an odd number of cylinders, and the firing interval must be twice the angle between adjacent cylinders.

Choice of Type

Of the various types mentioned, the vertical engine is inclined to be long and heavy, since each cylinder must have a separate crank and its own section of the crankcase. The radial engine is inherently of light weight and lends itself particularly well to air cooling. Furthermore, it is relatively simple and particularly easy to overhaul and repair, even when the engine is in place in the airplane. These advantages tend to offset its obvious disadvantage in regard to frontal area, and it is now the most widely used type of all. The four-cylinder and six-cylinder opposed engine is widely used in small airplanes. Liquid-cooled engines are now usually built as 12-cylinder V engines or 24-cylinder H engines.

It cannot be said that any one of the types listed is best for all airplanes. The type selected for a given airplane depends on a great many considerations. In general, however, four- and six-cylinder air-cooled opposed engines are used up to about 300 hp, and from 300 to 1,200 hp the single-row air-cooled radial is most popular. Above this power range two-row radials and 12-cylinder liquid-cooled V engines are used, while the highest power ratings call for multirow radials or H-type engines.

TYPICAL ENGINES

Examples of the more popular types will now be described in some detail. Table 4 gives additional data on these and many other engines.

Continental C-85 Engine

This is a 4-cylinder opposed air-cooled engine (Fig. 83) rated at 85 hp at 2,575 rpm. It is widely used in light two- and three-place airplanes.

Cylinders. Each cylinder has a bore of $4\frac{1}{16}$ in. and a stroke of $4\frac{1}{16}$ in., giving a total piston displacement of 188 cu in. Cylinder barrels are made of steel, screwed and shrunk into cast-aluminum cylinder heads.

Valves. The two valves per cylinder are operated by push rods from a single horizontal camshaft located in the crankcase below and

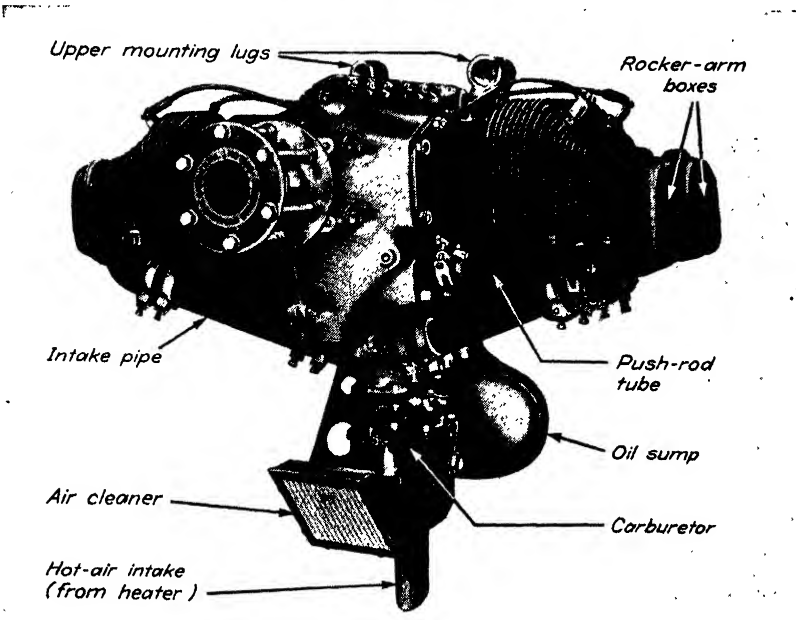


FIG. 83. Continental C-85 engine. (*Continental Motors Corporation.*)

parallel to the crankshaft. The valve gear is fully enclosed and automatically lubricated.

Pistons. Pistons are of cast-aluminum alloy with cast-iron rings. Piston pins are of steel.

Connecting Rods. These are steel forgings with removable caps to allow assembly around the crankpins. The piston-pin end of each rod is bushed with ordinary bronze, while the crankpin end carries a lead-bronze bearing.

Crankshaft. The crankshaft has three lead-bronze bearings, with two opposed cranks between each pair. Propeller thrust is taken on the flanged end of the front bearing.

Crankcase. The crankcase is made of two aluminum-alloy castings, bolted together along a vertical plane passing through the crankshaft

axis, together with a third casting, or cover, at the rear end. Half of each main crankshaft bearing is carried in each main part of the crankcase. On the crankcase rear cover are *lugs* for the attachment of the engine to the airplane structure.

Lubrication is by a pressure system in which oil is fed to the main bearings and camshaft bearings by a gear-type pump driven from a spur gear on the rear end of the crankshaft. From the main bearings, the oil passes to the crankpins through tubes inserted in holes drilled in the shaft. Cylinder bores, pistons, piston pins, and cams are lubricated by oil thrown off the crankpins and connecting rods. Valve tappets, which are of the hydraulic type, are lubricated under pressure from the oil pump, and from these oil is delivered through the hollow push rods to the rocker arms and valve stems. Excess oil from all lubricated parts drains to the crankcase and from there to a small oil tank or *sump* bolted to the crankcase at the bottom rear. The oil pressure in the passages leading from the pump to the bearings is regulated by a spring-loaded *relief* valve similar to the safety valve on a boiler. The overflow from this valve discharges into the crankcase.

Auxiliaries. Two magnetos are mounted on the rear crankcase cover and are driven from the crankshaft. A tachometer drive is provided on the oil pump. A vertical carburetor is attached to the junction of the inlet pipes below the engine.

Cooling. The cylinders, which are well finned, are cooled by air taken from behind the propeller. Baffles are incorporated in the engine cowl in such a way as to cause the air to flow from the top of the engine between the cylinders and through the cylinder fins into a compartment below the engine, from which the air is discharged to the atmosphere through a suitable slot (see Fig. 95).

The Wright Cyclone Engine

The Wright Cyclone engine is a 9-cylinder air-cooled radial engine rated up to 1525 hp at 2,800 rpm. It is used in both military and commercial airplanes. An exterior view is shown in Fig. 84 and a cross section of the engine is shown in Fig. 85.

Cylinders. Each cylinder has a bore of 6⅛ in. and a stroke of 6⅞ in., giving a total piston displacement of 1,823 cu in. The cylinder barrels are made of steel forgings, open at both ends. Near the lower end of each barrel is a flange for bolting to the crankcase, while the upper end is threaded to fit the forged aluminum-alloy cylinder head, which is screwed upon it. The cylinder head contains the valves and valve ports and the steel valve seats. Both cylinder barrel and head

are equipped with fins for air cooling. Those on the head are machined while those on the barrel are of sheet aluminum, fastened in grooves on the barrel by a special rolling process (Ref. E11).

Cooling. Radial engines are generally used with tractor propellers and are mounted in *cowls* such as those shown in Fig. 94.

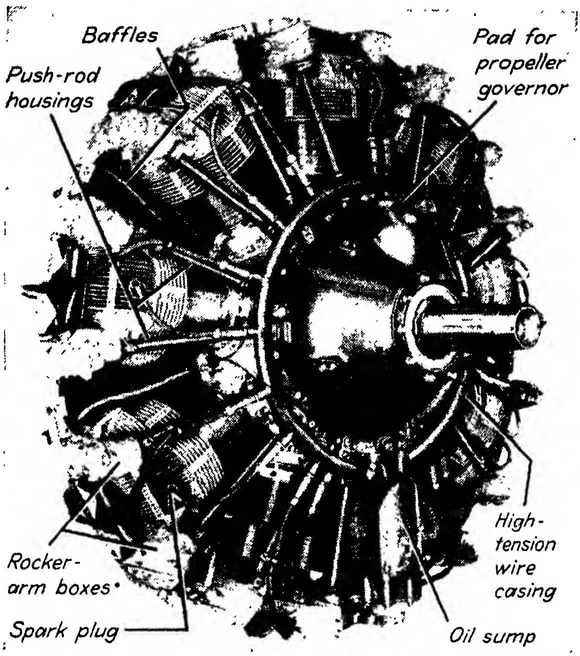


FIG. 84. Wright Cyclone nine-cylinder radial air-cooled engine. (*Wright Aeronautical Corporation.*)

Valves. There is one intake and one exhaust valve in each cylinder, operated through push rods and rocker arms from a cam located in the front part of the crankcase. The cam is driven by gears from the crankshaft. The entire valve gear, including valve springs, rocker arms, and push rods, is enclosed and automatically lubricated.

Pistons. The pistons are forged of a special aluminum alloy. They each carry five rings and a hardened-steel piston pin. The pin "floats," *i.e.*, it may turn in both the piston and the connecting rod. To prevent the piston pin from sliding sideways and "scoring" the cylinder, the piston is provided with aluminum plugs in each end.

Connecting Rods. A photograph of the connecting rods as assembled in a radial engine is shown in Fig. 86. One of the connecting rods, shown at the top in the photograph, carries the big-end bearing

and is called the *master* connecting rod. The bearing in this connecting rod is lined with a special silver-lead material where it bears on the crankpin. The portion of the rod surrounding this bearing is equipped with holes to receive the *hinge* pins. Each of the other

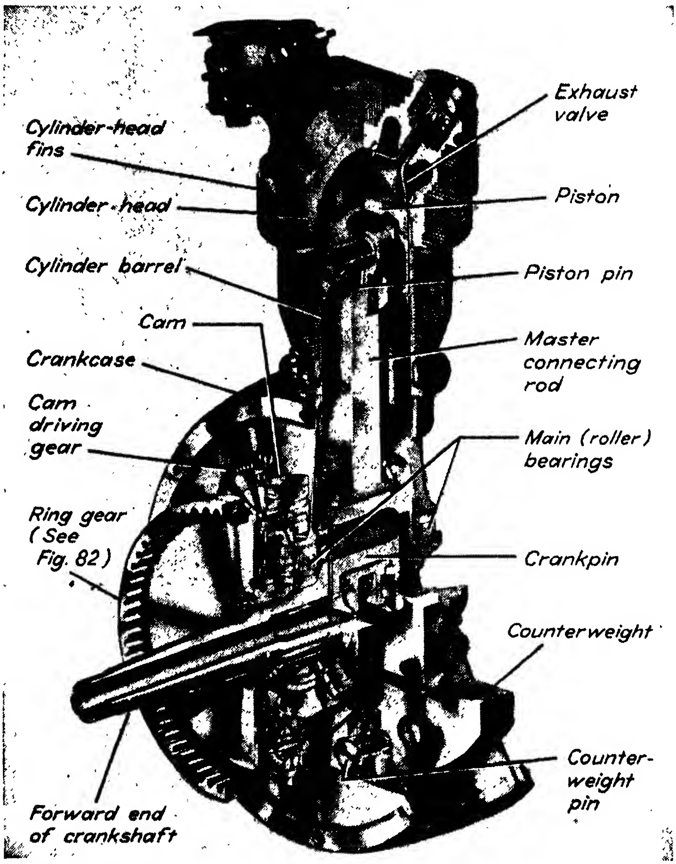


FIG. 85. Cutaway section through No. 1 cylinder of Wright Cyclone engine. (Propeller reduction gear and supercharger sections omitted.) (*Wright Aeronautical Corporation.*)

cylinders has an *articulated* connecting rod, which is connected by means of a hinge pin to the master connecting rod. Each of the connecting rods, master or articulated, is connected to the piston at its outer end by means of a piston pin.

Crankshaft. The crankshaft is made in two parts from alloy-steel forgings and has a single crankpin, counterbalanced with *counter-*

weights. The counterweights are mounted on special bearings so that they are free to move slightly with respect to the crankshaft. This arrangement reduces torsional vibration of the shaft (see Ref. E12). The two parts of the shaft are held together by a split and bolted connection just behind the connecting-rod bearing (see Fig. 85). This construction is necessary in order to assemble the master connecting

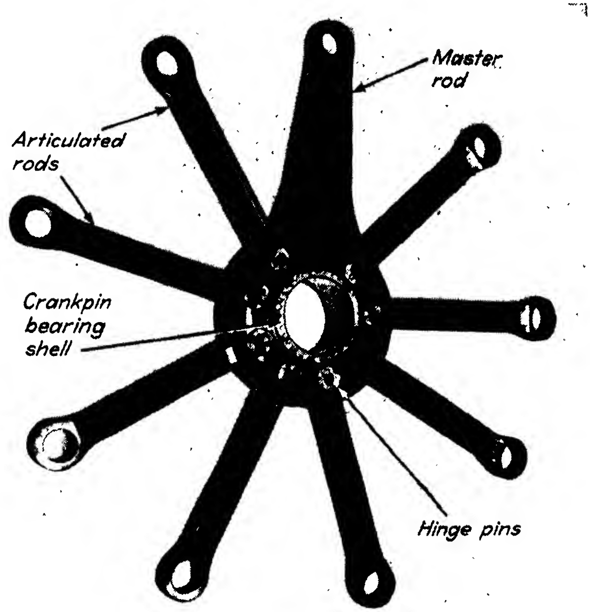


FIG. 86. Master and articulated connecting rods of the Wright 18-cylinder engine. (*Wright Aeronautical Corporation.*)

rod on the shaft or to remove it for repairs. In some radial engines the crankshaft is in one piece and the big end of the master rod is made in two parts for assembly and disassembly. On either side of the crank is a roller bearing. The crankshaft is hollow and has oil passages to supply the bearings.

Reduction Gear. This is of the planetary type and is similar to that shown in Fig. 82. The propeller shaft is supported on the long front end of the crankshaft and on a large ball thrust bearing. At its rear end it carries a frame on which the planetary pinions are mounted. These are driven by a large internal gear mounted on the crankshaft, and they also mesh with the stationary sun gear fastened to the front part of the crankcase. The propeller shaft is provided with internal

oil passages for operating a hydraulic controllable-pitch propeller. There is a mounting and drive on the front of the crankcase for a constant-speed-propeller control (see Fig. 84), which consists of a small centrifugal governor controlling the flow of oil to the pitch-changing mechanism.

Crankcase. The crankcase is made in six sections. The front section contains the thrust bearing, reduction gear, and valve gear. The *power section* is composed of two steel forgings which are bolted together in the plane of the cylinder axes. Each of these parts carries one of the main crankshaft bearings and one-half of each *pad*, to which the cylinders are bolted. Together, these two parts house the crank and connecting rods. The section immediately behind the power section carries the supercharger housing and inlet manifold and *bosses* for attaching the engine to its mount. The *rear section*, in two parts, carries the supercharger and auxiliary drive mechanism and also the carburetor, magnetos, pumps, etc. The front section is of forged aluminum alloy, the power sections are steel forgings, and the other sections are cast from magnesium alloys.

Mounting. The nine bosses for the bolts which hold the engine in the airplane are cast, one on each intake-pipe connection.

Intake System. The downdraft injection carburetor, located over the rear of the crankcase, delivers the mixture of air and fuel to the inlet side of the centrifugal supercharger, which is driven from the crankshaft through a train of spur gears. The blower is furnished with a single-speed drive, or it can be furnished with a two-speed gear for both low- and high-altitude operation.

Lubrication. An oil pump, driven from gears on the rear of the crankshaft, takes oil from an external tank and delivers it through a strainer to the central passage in the crankshaft and through suitable passages to the various gears and bearings. Oil passes to the master-rod bearing through a hole in the crankpin. Some of the oil escaping from this bearing is collected by "end seals" and delivered to the hinge-pin bearings. The pistons, piston pins, and cylinder walls are lubricated by oil thrown from the crankpin bearing. Oil drains to the *sump* at the bottom of the power section of the crankcase, from which it is drawn off by the scavenging pump and returned to the external oil tank. The cylinders are made so as to project into the crankcase, as shown in Fig. 85, so that the oil which drains to the bottom of the case will not flow into them. While the engine is running, a great deal of oil is thrown into the open cylinder ends, but the motion of the piston throws most of it out again immediately. For this reason inverted cylinders, as a rule, consume no more oil than upright ones.

Ignition. Each cylinder has two spark plugs, and there are two magnetos, one for each set of plugs. The magnetos are mounted on the rear crankcase section and are driven through gears from the crankshaft. The wiring from the magnetos to the spark plugs is *shielded*, *i.e.*, covered with metal to prevent interference of the ignition system with radio reception.

Auxiliaries. In addition to the magnetos and carburetor, the rear crankcase section carries the fuel and oil pumps, the tachometer drive,

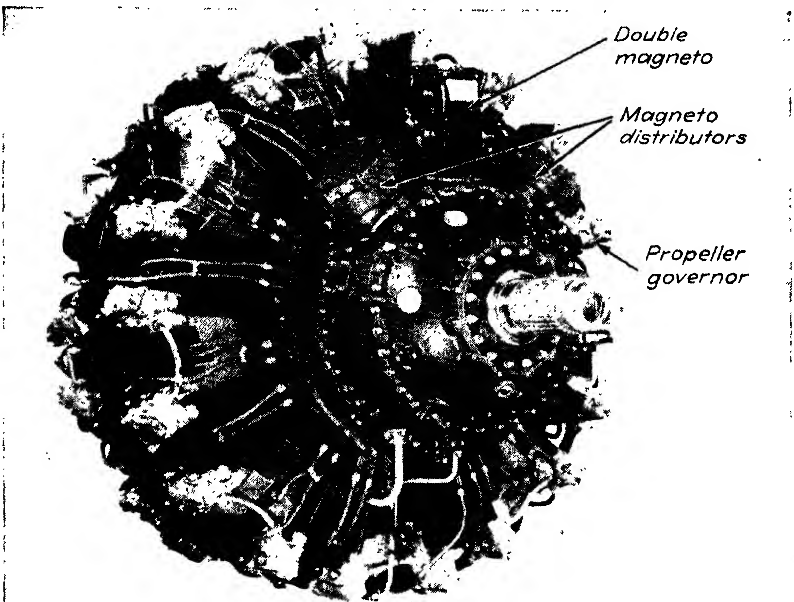


FIG. 87. Pratt and Whitney Double Wasp. *(Pratt and Whitney Aircraft Division, United Aircraft Corporation.)*

and pads for a standard-type starter, generator, vacuum pump, hydraulic pump, etc. For military purposes, provision is made for mounting machine-gun synchronizer drives on the rear crankcase section. These are for the purpose of timing the machine guns so that they will fire between the blades of the revolving propeller.

Exhaust Manifold. This engine is usually fitted with a ring-shaped exhaust manifold mounted behind the engine under the cowl.

THE PRATT & WHITNEY DOUBLE WASP

The Pratt & Whitney Double Wasp is shown in Figs. 87 and 88. It is an 18-cylinder, two-row, radial, air-cooled engine, rated at 2,400 hp

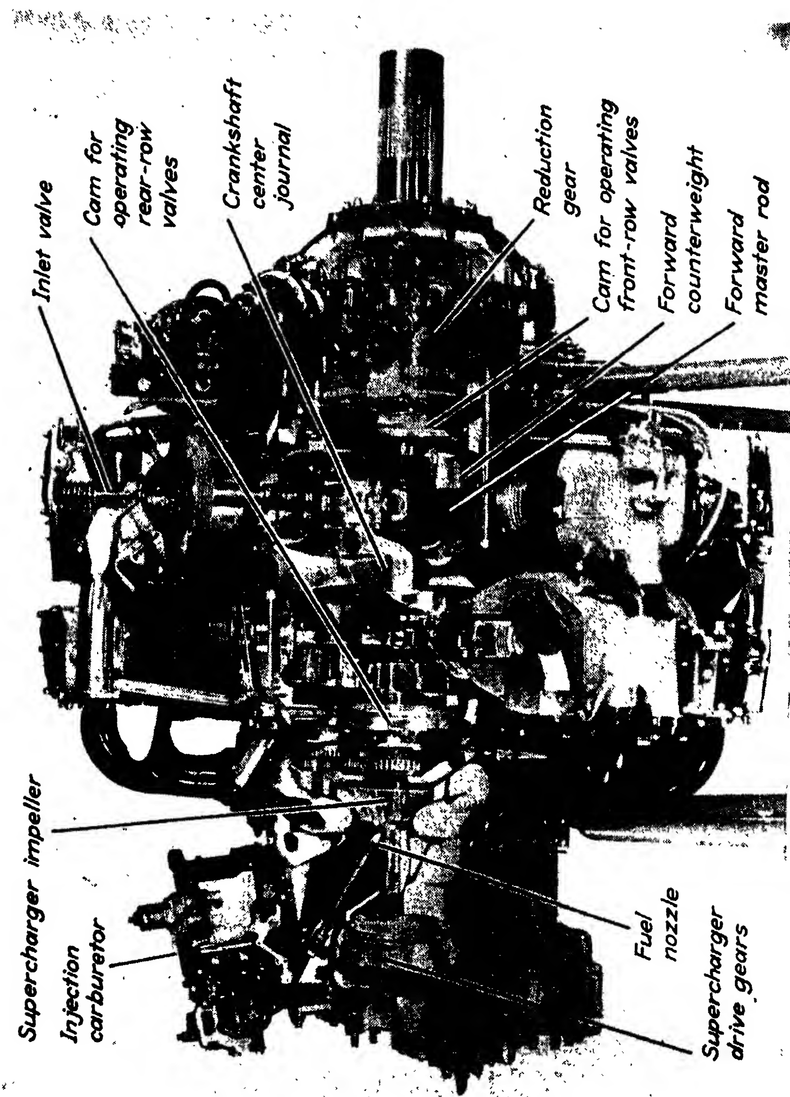


FIG. 88. Pratt and Whitney Double Wasp cutaway exhibition model. (*Pratt & Whitney Aircraft Division, United Aircraft Corporation.*)

at 2,800 rpm for take-off. In its general structure it is quite similar to the Wright Cyclone already described, but there are certain differences in arrangement due to the two-row construction and several differences in detail.

Crankshaft. The crankshaft has two cranks, set at 180° from each other, each carrying one counterweight. The crankshaft is built up of three pieces, splined and bolted together, and is carried in three main bearings of the journal type.

The main sections of the crankcase are made of forged aluminum alloy.

Valve Gear. There are separate valve-gear mechanisms in front and rear, to serve the front row and rear row of cylinders respectively.

Secondary Balance Weights. This engine is fitted with two weights, each rotating at twice engine speed, for the purpose of offsetting the unbalance caused by the master connecting rods. These weights are located at either end of the crankshaft (near the cams) from which they are driven by small spur gears.

Earlier models of this engine were used in the Thunderbolt, Corsair, and Hellcat fighters, as well as in several other types, during the Second World War. It now powers the DC-6 transport airplanes.

Bristol Centaurus

This is an 18-cylinder two-row radial rated at 2,825 hp for take-off. Figure 89 is a front view of this engine and Table 4 gives its important characteristics. The unique feature of this, and other Bristol engines, is the use of sleeve valves instead of poppet valves (see Fig. 69 and accompanying discussion). The sleeves are driven by cranks in the manner already described. Each sleeve is fitted with exhaust and intake ports, which register at the proper time with corresponding ports in the outer shell.

The **cylinder head** is a finned member which is bolted to the shell and projects down into the upper end of the sleeve, carrying "junk rings" (see Fig. 69) to prevent leakage at this point.

Except for the above features, the general structure of this engine is similar to those of the radial engines previously described. The Centaurus is used in several large British transport planes.

Pratt & Whitney Wasp Major

Figures 90 and 91 illustrate the largest reciprocating engine now in service use, the Pratt & Whitney Wasp Major. This is a 28-cylinder,

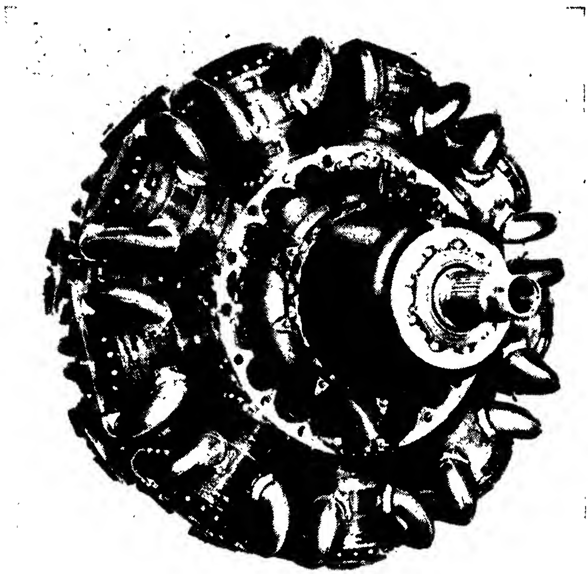


FIG. 89. Bristol Centaurus, sleeve-valve engine. (*Bristol Aeroplane Co., Ltd.*)

FIG. 90. Pratt & Whitney Wasp Major 28-cylinder engine. (*Pratt & Whitney Aircraft Division, United Aircraft Corporation.*)

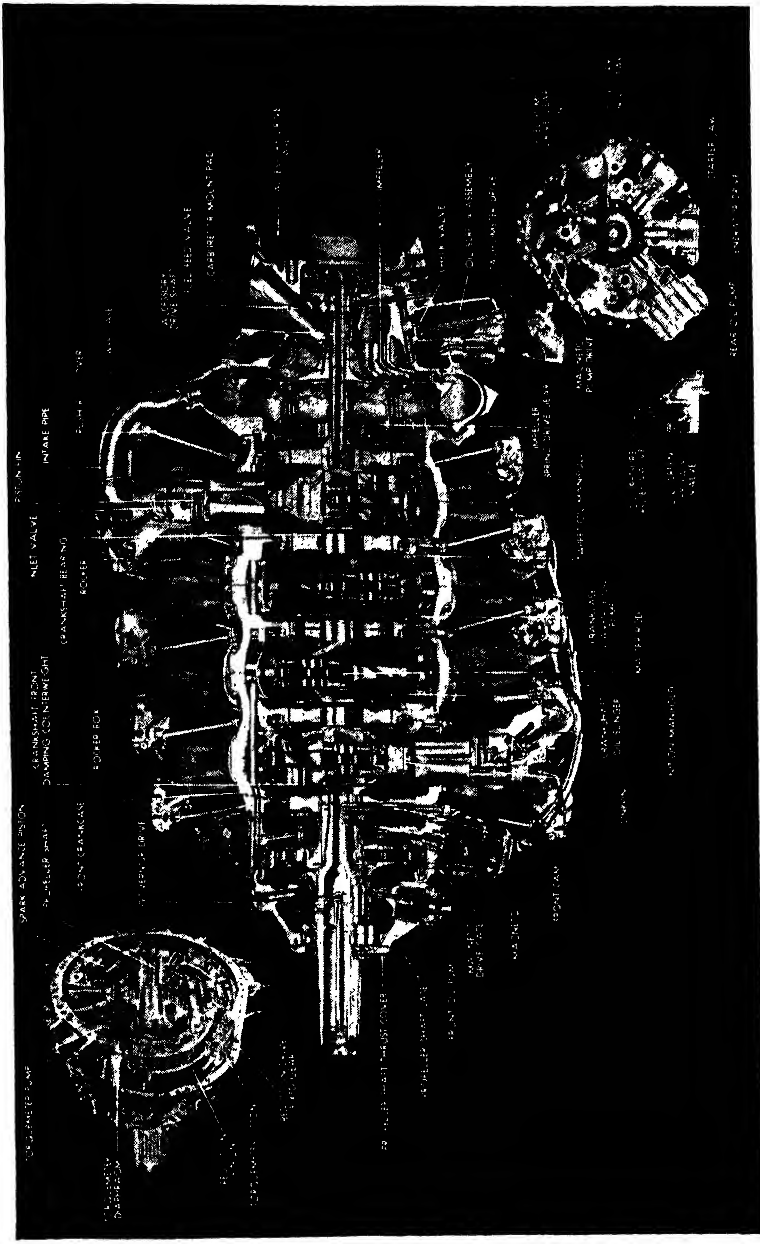


Fig. 91. Pratt & Whitney Wasp Major engine, cutaway model. (*Pratt & Whitney Aircraft Division, United Aircraft Corporation*)

four-row, air-cooled radial engine rated at 3,500 hp at 2,700 rpm. for take-off.

Each circular row of cylinders is staggered, or offset with respect to the row ahead, which gives the engine its unique appearance. The intake ports and intake manifolds are on top of the cylinder heads, while the exhaust ports are at the side of each head, facing at an angle toward the rear.

The crankshaft is a single-piece forging carrying four cranks and five journal bearings. It is counterweighted at the front and rear ends only, since this is all that is required to give the engine excellent balance.

Since the crankshaft is in one piece, the master connecting rods must be split and bolted together around the crankshaft. An unusual feature is the use of seven double magnetos, one for each line of four cylinders (see Fig. 90). In other details, this engine is very similar to the Pratt & Whitney Double Wasp already described. Several new transport and bomber airplanes are being developed to use four or more of these large engines.

The Packard Rolls-Royce

Designed in England and produced there as well as in the United States, the Rolls-Royce engines are unquestionably the leading liquid-cooled aircraft engines of the present time.

The Packard Rolls-Royce, illustrated in Fig. 92, is the British Merlin with minor modifications. Its latest military rating is 2,200 hp for take-off, using water-alcohol injection. (It was originally designed to be a 750-hp engine!)

The cylinders, which have a bore of 5.4 in. and a stroke of 6 in. are made in two *blocks* of six each. Cylinder heads with their water jackets and valve ports are formed by a single aluminum casting for each block, into which the steel cylinder barrels are inserted. The barrel water jackets are also in a single casting for each block. Each block is fastened to the crankcase by long *studs*, with nuts located at the top of the cylinder-head casting. The crankshaft is a one-piece forging carrying six cranks and seven main bearings. Two cylinders, one from each block, operate on each crank through "forked and plain" connecting rods. The crankcase is an aluminum casting. A spur reduction gear (see Fig. 80) is fitted at the front end of the engine.

A unique feature of this engine is the two-stage two-speed gear-driven supercharger, mounted at the rear, which receives fuel-air mixture from the carburetor and delivers it to the inlet manifolds through

a liquid-cooled *aftercooler* built into the engine. Thus, this engine requires a coolant radiator for the aftercooler as well as for the cylinder-jacket liquid.

This engine is fitted with an automatic control assembly (see figure) which sets the fuel-air ratio, spark timing, and supercharger gear ratio in accordance with engine speed, altitude, and throttle position, thus relieving the pilot of these duties.

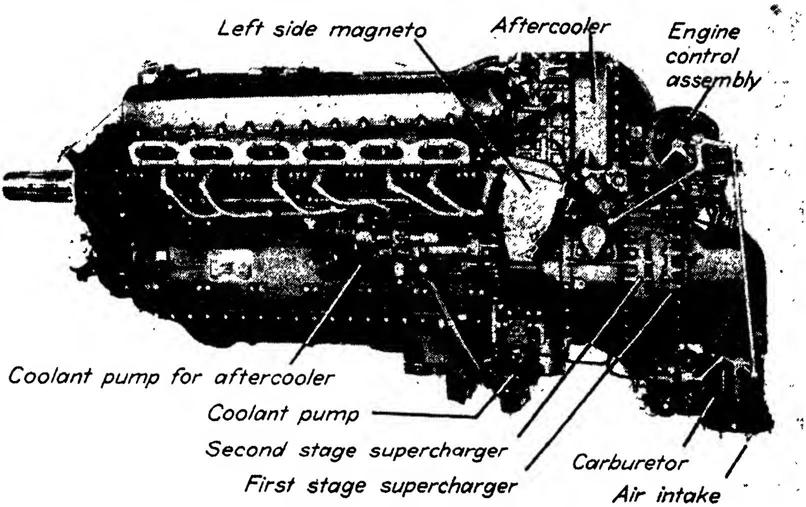


FIG. 92. Packard Rolls-Royce engine. (*Packard Motor Car Company.*)

It was earlier models of the Rolls-Royce Merlin that powered the famous Spitfire and Hurricane fighters which won the Battle of Britain and played such an important role throughout the Second World War. The Packard Rolls-Royce powered late models of the famous P-51 Mustang fighter.

ROLLS-ROYCE EAGLE

Figure 93 shows a side view of the 24-cylinder, sleeve-valve, H-type Rolls-Royce Eagle, recently announced by that British company. It is rated at 3,500 hp for take-off. Like the Merlin and Packard Rolls-Royce, this engine carries a built-in liquid-cooled aftercooler served by a two-stage supercharger.

A notable feature of this engine, in addition to the sleeve valves, is that it is fitted with two concentric propeller shafts for use with *contrarotating* propellers (see Chap. X). The engine is apparently intended chiefly for military fighters.

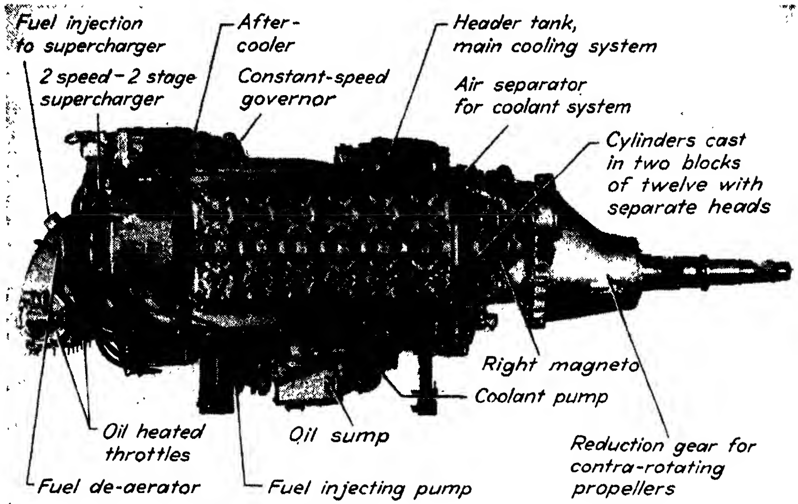


FIG. 93. Rolls-Royce Eagle 24-cylinder sleeve-valve engine. (*Rolls-Royce, Limited.*)

ENGINE INSTALLATION

As the engine is installed in an airplane, it requires in addition to the elements aready described, the following:

Cooling system
Fuel-supply system
Oil-supply system
Air-inlet system
Exhaust system
Starting system
Control system
Fire-extinguishing system

Cooling-system Details

Air Cooling. Air-cooled engines must be provided with a cooling-air intake, with air passages or baffles to direct the air around the cylinders and between the fins, and with a suitable outlet to discharge the heated air to the atmosphere. It is general practice to rely chiefly on the velocity of the airplane and of the propeller slipstream to furnish the necessary air circulation, although in some cases a fan, or an exhaust ejector, is used to augment the flow thus obtained. The air intake is located in a region of relatively high dynamic pressure, and the outlet in a region of low pressure. The detailed arrangement of

the cooling system depends considerably on the form of the engine. Several typical arrangements will be described.

Radial-engine Cooling. Figure 94 shows the general method of cooling radial engines, by means of air passed through a circular cowling. This figure shows a cross section of the cooling passages including the baffles, which are used to force the air to pass between the fins at the rear of the cylinders. In flight, the circular entrance at the front

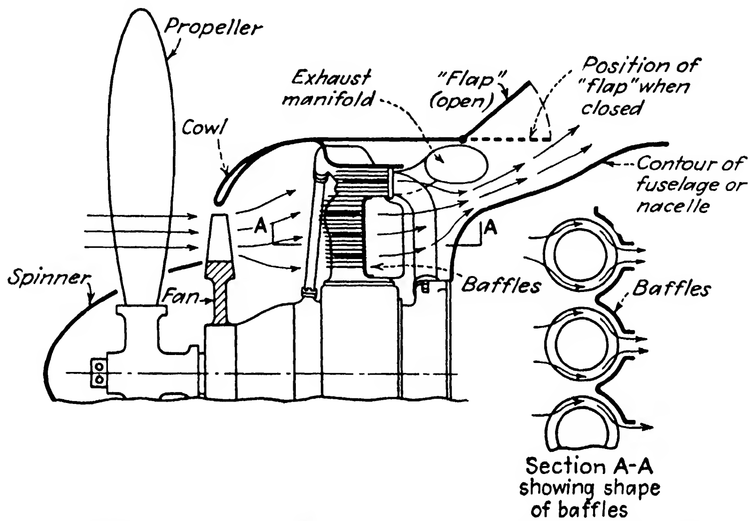


FIG. 94. Diagram showing cooling-air flow in tractor installation of a radial engine. (Arrows indicate direction of flow. Only the upper half of the engine is shown.)

is in a region of high dynamic pressure, and the annular outlet is in a region of negative pressure.

At high airplane speeds, considerable pressure difference is available to cause a rapid flow of air through the system. Since the drag of the system increases rapidly with increasing rate of airflow under the cowl, in most cases the size of the outlet slot is restricted to that necessary for the level-flight condition, and controllable flaps around the trailing edge of the cowl are provided for the purpose of increasing the airflow during climb. Figure 94 shows a cross section of such a flap, and Fig. 184 shows the appearance of an engine nacelle when the flaps are extended in the climbing position. Naturally, the drag of the flaps is large in the open position, but the drag with the flaps closed is considerably less than it would be for a fixed cowl designed to supply adequate cooling in climb. The use of flaps is general in airplanes where high speed is of particular importance.

Fan Cooling. In some cases flow through the system shown in Fig. 94 is augmented by a fan located in the cowl entrance as indicated. The fan may be mounted directly on the propeller shaft, although it is more effective if operated at higher than propeller speed, through gearing. The angle of the fan blades is such that it assists airflow at low airplane speeds only, and is substantially *neutral* at high speeds where it is not needed. Fan cooling has the advantage of absorbing less power than the open flaps for a given airflow at low speeds. The

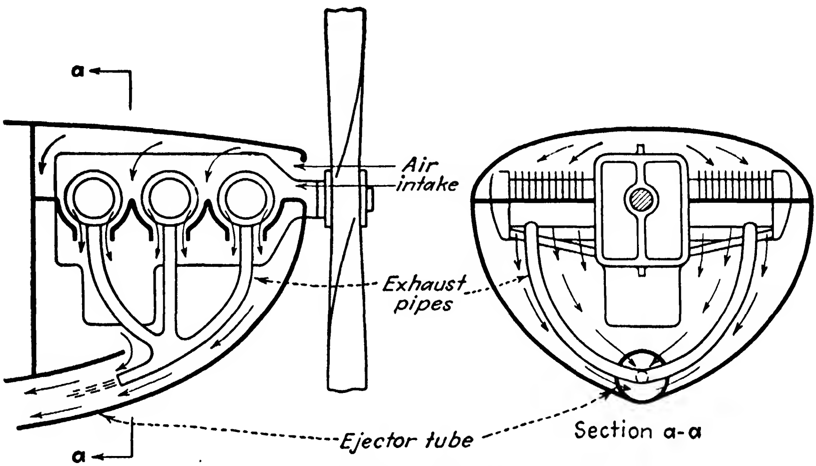


FIG. 95. Cooling system for opposed engine, with exhaust ejector. Arrows show path of cooling air.

German Fokke-Wulff 190 pursuit plane used such a fan, operating at about three times propeller speed.

Opposed-engine Cooling. Figure 95 shows a typical cooling system for this type of engine. Air enters through openings in front and builds up a pressure in the upper part of the cowling. This pressure causes the air to flow downward around the cylinders and through the fins to the lower part of the cowling, from which it flows to the atmosphere through a bottom opening. In the case illustrated, use is made of an *exhaust ejector.* This is arranged so that the blast of exhaust gas assists the flow of air through the system. By this means adequate cooling is obtained at low flight speeds and on the ground. Only a few installations of this kind use the ejector (see Ref. E3).

Vertical-engine Cooling. Vertical engines are cooled by the same means as opposed engines, except that the air is taken in on one *side* of the engine at the front, passes across through the baffles and fins to the

other side, where it is discharged through a suitable slot near the rear of the cowling.

Pusher engines are cooled by means similar to those used for tractors, but here the flow must usually be augmented by a fan or exhaust ejector, since on the ground and at low flight speeds the propeller is of little assistance in promoting flow through the system.

Liquid-cooling Systems. The cooling system required for liquid-cooled engines consists of the radiator, liquid storage tank, piping, air passages, valves and controls, in addition to the pump, piping, and jackets which are carried on the engine itself.

Radiators. The radiator is essentially an arrangement for receiving the hot liquid from the engine jackets and sending it through small tubes or thin sheet-metal passages whose outer surfaces are exposed to a blast of air. In this way, a very large surface in contact with the liquid on one side is exposed to the cooling action of the air on the other side. Radiators are made in a great variety of shapes and sizes, but they all comprise three essential elements: (1) an intake *header* which collects the liquid from the engine and distributes it to the various cooling elements of the radiator; (2) the cooling elements or tubes, and (3) an outlet header which collects the liquid from the cooling elements and delivers it to a pipe, through which it runs back to the engine.

Radiator Cowling. At a given set of temperatures at a given air density, the heat dissipated by a radiator is nearly proportional to the velocity of the air through its core. The power required to force the air through the core, however, varies approximately with the cube of the air velocity. Thus, by reducing the air velocity through the core, the ratio of heat dissipated to power absorbed is reduced, even though the size of the radiator must be increased correspondingly to dissipate the heat from a given engine installation. In practice, it is therefore desirable to use as large a radiator as is consistent with weight and space considerations, in order to secure the necessary cooling with a relatively low air velocity. The velocity through the core is reduced below that of the air stream by enclosing the radiator in a streamlined housing such as that shown in Fig. 96. The air exit of this housing is controlled by a flap as shown. For the most severe cooling conditions, this flap is wide open. For less severe conditions, it may be partly closed, which reduces the drag at the same time that it adjusts the cooling to fit the new conditions. The flap may be controlled automatically by means of a thermostatic device operating on the cooling-liquid temperature.

In order to minimize radiator size, it is important to use the maxi-

mum feasible temperature of the cooling medium. This reduces the amount of heat dissipated by the engine and also the amount of radiator surface required. This is the reason for using cooling liquids with high boiling temperatures. The cooling liquid used at the present time consists of a solution of 50 to 75 per cent ethylene glycol in water. Use of this liquid allows operation at temperatures up to 250°F with-

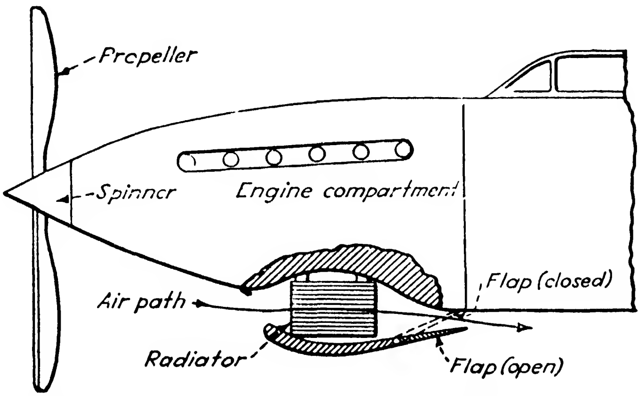


FIG. 96. Section through radiator and radiator housing of a modern liquid-cooled engine installation.

out danger of boiling, and also ensures a freezing point low enough to avoid trouble from this source.

Choice of Cooling System. *Weight.* In general, air-cooled and water-cooled engines of the same power and of equally good design have about the same weight. This means that the liquid-cooled engine installation weighs more than the air-cooled installation of equal power by the weight of radiator, piping, and cooling liquid—a matter of 0.2 to 0.3 lb per rated horsepower.

Drag. In general, the drag of an air-cooled installation is greater than that of a liquid-cooled engine of equal power for two reasons: (1) the air-cooled engine itself is usually of greater frontal area, and (2) the cooling surface is always located on the cylinders, whereas in the liquid-cooled installation it can be located and cowled in the manner giving lowest drag, quite independently of the engine position.

Maintenance and Reliability. Here air cooling has a great advantage, since it involves no possibility of trouble from leaks, boiling, or freezing. These considerations have led to the general use of air-cooled engines for training and for private and most commercial flying.

For military service in addition to these advantages, the air-cooled installation appears to be somewhat less vulnerable to machine-gun

fire. Thus, for military types which operate at low altitudes, air cooling is generally preferred. In fact, the only place where liquid-cooled engines appeared to advantage in the Second World War was for high-altitude fighters such as the Spitfire, P-51, and Messerschmitt. The advent of the turbojet engine, however, has probably rendered the reciprocating engine obsolete in most fighter types.

Fuel-supply Systems

The fuel-supply system consists of fuel storage tanks, fuel piping, control valves, and fuel pumps. It usually includes, also, one or more fine screens or strainers, intended to prevent the introduction of foreign matter to the carburetors or fuel pumps.

Tanks. Airplane fuel tanks are made of aluminum, plastic material, or ordinary steel tin-plated. Aluminum tanks are built up by welding. Tinned-steel tanks are easily soldered and are considerably less expensive than aluminum tanks. They are very popular for low-priced airplanes. All fuel tanks, except the very smallest, are divided into compartments by *baffle plates*, running across the inside of the tank in two directions. The function of these baffle plates is to keep the fuel from surging in the tank and also to brace the sides of the tank and keep them from bulging. Large holes are cut in the baffles at frequent intervals so that the fuel can flow freely between them. Tanks must be provided with a filler cap at the top and with fuel-outlet connections so located that fuel can flow from the tank in any normal attitude of the airplane. Strainers are often incorporated in the tank's outlet connections.

Wing-structure Tanks. Sometimes a metal wing itself is used for fuel storage (see Fig. 97). The joints behind the front spar are made up with strips of fabric impregnated with artificial rubber as a gasket material to ensure tightness. The ribs form the necessary baffles, and solid ribs are used to close off the ends of the tank compartment.

Plastic Tanks. Another method of storing fuel in the wings is to insert a bag made of plastic material in the wing structure. Since such tanks cannot be baffled, they must be made in small units to avoid trouble from surging of the fuel.

Bulletproof Tanks. The fuel tanks of modern military airplanes are made "bulletproof" by means of a lining of some soft material which acts to close up holes made by machine-gun bullets. When the material is punctured, the fuel which gets into the "wound" causes it to swell and close the hole. One successful material of this kind consists of layers of fabric impregnated with soft artificial rubber.

Fuel-tank Mounting. Since fuel tanks are made of very thin material, they are quite delicate and must be carefully protected from accidental injury, from vibration, and from chafing against their mounting members. To this end, tanks are so located as to be protected by the airplane framework and bulkheads, and the mounting usually takes the form of a *cradle* made up of metal strips lined with felt where they come in contact with the tank walls.

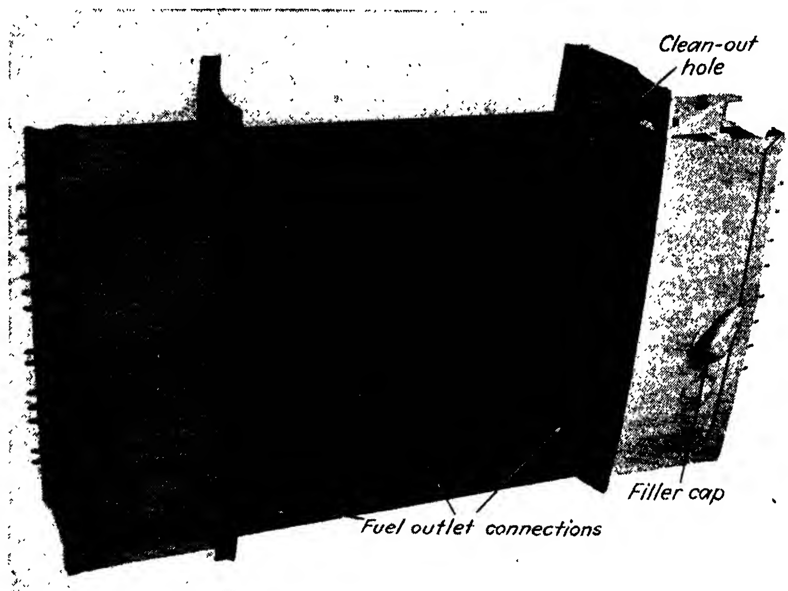


FIG. 97. Airplane fuel tank, wing-section type. (Tank is formed between wing spars and wing ribs.) (*Chance Vought Aircraft Division of United Aircraft Corporation.*)

Fuel Piping. Aluminum tubing is generally used for fuel lines. It is very important that the joints between the piping and other parts of the fuel system be very carefully made to prevent breaking in flight due to vibration or other causes. For the part of the fuel line that runs between the engine and the airplane structure, where it is subject to severe vibration, it is necessary to use a special artificial-rubber hose, compounded so as to be very resistant to the solvent action of gasoline.

Fuel Feed. Whenever possible, the airplane designer locates the fuel tanks far enough above the carburetor so that a fuel pump will not be required. Pumps, like any other mechanical contrivance, are subject to failure, while fuel feed by gravity is very reliable. Unfor-

tunately, it is not usually practicable to locate the tanks for gravity feed, and in such cases pumps are necessary.

Fuel Pumps. Airplane fuel pumps are usually of the gear or vane type, although plunger or diaphragm pumps are sometimes used. Pumps are usually mounted on and driven by the engine but may be driven by electric power in large airplanes.

In order to avoid "vapor lock," *i.e.*, the formation of fuel vapor in the lines, large airplanes with long fuel lines are fitted with electrically

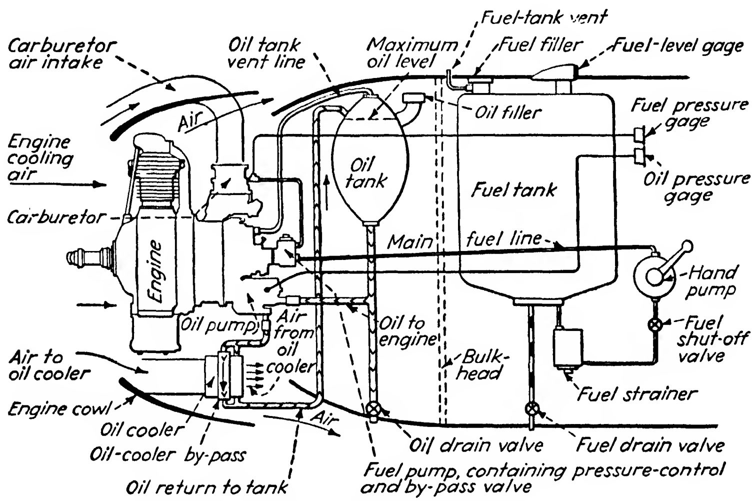


Fig. 98. Diagram of typical fuel and oil systems.

driven *booster* pumps, which are located at the bottom of each tank and keep the fuel lines under moderate pressure at all times. The fuel systems of large airplanes with many tanks are quite complicated because the tanks are usually connected so that the fuel in any tank is available to any one of the engines. Furthermore, in all airplanes there must be duplication of pumps so that in case one pump fails there will be others quickly available to take up its load.

Oil-supply System

Except for wet-sump engines, an external oil tank is necessary, together with piping and an oil cooler. The tank is so designed that it can never be entirely filled with oil, for some space must always be left at the top for the oil to expand when it becomes heated. This space must be vented to the atmosphere, usually through the engine crankcase. From the bottom of the tank a pipe is led to the engine-

oil-pump inlet, and from there the oil is distributed to the bearings, as previously explained. The scavenging pumps take the oil from the crankcase and return it to the oil tank.

The oil cooler is a small radiator similar to a water radiator. The cooler is generally located in the line between the scavenging pumps and the oil tank. It is usually fitted with a spring-loaded by-pass valve which short-circuits the cooler when the oil is cold and "thick" and passes through the cooler with difficulty. Sometimes the by-pass is controlled according to the oil temperature, by means of a thermostatic valve which by-passes the oil as long as it remains below the normal working temperature. This is desirable since it makes possible quick warming of the oil when the engine is first started. Aluminum tubing is generally used for oil lines, and rubber connections are employed to prevent vibration strains on the tank and piping. Figure 98 shows a typical oil system for a small single-engine airplane.

Air-inlet System

The air for combustion is taken from the atmosphere through ducts opening forward. The system would be very simple if it were not for the fact that under certain atmospheric conditions the air must be heated in order to prevent ice formation in the carburetor or in other parts of the system. Usually two air-supply passages are available for each engine. One of these takes atmospheric air as it comes, and the other passes the air through exhaust-heated passages before it reaches the engine air intake. The pilot or flight engineer operates a control which puts one or the other passage into use, as required by circumstances. The use of the heated air entails some sacrifice in maximum power, since the inlet density is thereby reduced.

Exhaust System

Except where "jet stacks" can be used, exhaust gases from the cylinders are collected into a common manifold from which they are discharged at some suitable point to the atmosphere. For radial engines, the exhaust manifold is usually circular in form and is called a *ring*.

In high-speed military airplanes, especially fighters, the exhaust gases can be used effectively to assist in propelling the airplane. By using short pipes on each cylinder, discharging to the rear, an appreciable amount of *thrust* is obtained, owing to the reaction of the gases as they are blown out. At very high airplane speeds this thrust may be as high as 10 per cent of the propeller thrust (see also Chaps. IX and

X). As previously pointed out, the exhaust can be used to assist cooling airflow or to operate an exhaust turbine. In the latter case there is little thrust available.

Starting System

It is becoming almost universal practice to provide airplane engines with electric starters. Other types, including those using compressed air and those employing a powder charge, have been used in the past, but the electric starter has proved more satisfactory in the long run. Airplane starters operate exactly like automobile-engine starters, although they are generally lighter in proportion to their power and therefore of more expensive construction. Storage batteries and engine-driven generators to charge the batteries and to furnish current for other purposes are required, as in automobiles.

Control System

The controls necessary for the reciprocating-engine power plant always include a lever for operating the throttle, a valve for shutting off the fuel supply, and a switch for the ignition circuit. If variable spark timing, carburetor mixture control, or variable-speed supercharger are used, controls for these must also be provided. Other elements requiring control may be the cowl flaps, the propeller-pitch-changing mechanism, the fuel-system valves, pumps, etc.

Automatic Controls. As airplane power plants have developed, more and more control elements have been added, until it has become well nigh impossible for a pilot to give all of them adequate attention. For this reason, there is a growing tendency toward the use of automatic control mechanisms. Thus, thermostatic controls for water, oil, and inlet-air temperatures and automatic mixture controls, designed to give the proper fuel-air ratio at all altitudes, are used in the more elaborate installations. Automatic controls are considered especially important in single-place fighter airplanes where the pilot can have no assistance in the operation of his power plant (see Fig. 92 and accompanying description).

Fire-extinguishing System

All transport airplanes are required to have fire-extinguishing systems in connection with the engine installation. The principal engine fire hazard in flight is the danger of broken fuel, oil, or hydraulic lines. To take care of this eventuality, emergency valves are provided by means of which all these fluids may be shut off from the engine com-

TABLE 4. STATISTICS OF SOME TYPICAL RECIPROCATING AIRPLANE ENGINES, 1948

Manufacturer	Model	Cylinder arrangement	Number of cylinders	Cooling	Bore, in.	Stroke, in.	Displacement, cu in.	Propeller gear ratio	Compression ratio	Power ratings: Take-off: Hp	Power ratings: Take-off: Rpm	Power ratings: Take-off: Inlet pressure, in. Hg (abs.)	Power ratings: Maximum continuous: Hp	Power ratings: Maximum continuous: Rpm	Power ratings: Maximum continuous: Altitude, ft	Fuel octane number	Dry weight, lb	Lb/take-off hp
LIGHT-PLANE ENGINES (*unsupercharged*)																		
Continental Motors Corporation	C-85	Opp.	4	A	4 1/16	3 5/8	188	1.0	6.3	85	2,575	29*	85	2,575	SL	73	182	2.14
	E-185	Opp.	6	A	4	5	471	1.0	7.0	185	2,300	29*	185	2,300	SL	80	313	1.42
Aircooled Motors Corporation (Franklin)	4-A4	Opp.	4	A	4 1/2	3 1/2	225	1.0	7.0	100	2,600	29*	100	2,600	SL	80	214	2.14
	6A8	Opp.	6	A	5	4 1/4	500	1.0	7.0	225	2,600	29*	225	2,600	SL	80	382	1.69
Lycoming Division, Avco Manufacturing Corporation	GO-290	Opp.	4	A	4 7/8	3 7/8	289	0.64	7.5	170	3,400	29*	160	3,000	SL	91/98	323	2.02
	GO-435	Opp.	6	A	4 7/8	3 7/8	434	0.64	7.5	260	3,400	29*	240	3,000	SL	91/98	401	1.54
MEDIUM-POWER ENGINES																		
Continental Motors Corporation	R9a	R	9	A	5	5 1/2	972	1.0	6.3	525	2,300	41*	525	2,300	2,500	91/98	705	1.34
Pratt & Whitney Aircraft	Wasp Jr.	R	9	A	5 3/16	5 3/16	985	1.0	6.0	450	2,300	35*	450	2,300	SL	91/98	684	1.52
	Wasp	R	9	A	5 3/4	5 3/4	1,344	0.667	6.0	600	2,250	35*	550	2,200	5,000	91/98	953	1.60

MILITARY AND TRANSPORT ENGINES																	
Pratt & Whitney Aircraft..	Twin Wasp	2-R	14	A	5¾	6	2,180	0.438	6.5	1,800	2,800	60*	1,300‖	2,600	8,000	100/130§	1,870	1.04
													1,150‖	2,600	17,500			
	Double Wasp	2-R	18	A	5¾	6	2,804	0.450	6.7	2,400	2,800	60*	1,800‖	2,600	6,000	100/130	2,360	0.98
													1,600‖	2,600	16,000			
	Wasp Major	4-R	28	A	5¾	6	4,363	0.375	6.7	3,500	2,700	60*	2,800	2,550	3,500	115/145	3,482	0.99
Rolls-Royce, Limited......	Merlin	V	12	L	5.4	6	1,649	0.47	6.0	2,030†	3,000	80	1,770	3,000	4,000	115/145	1,740	0.86
	Griffon	V	12	L	6.0	6.6	2,239	0.44	6.0	2,500	2,750	82	2,060	2,750	2,250	100/130	1,980	0.79
	Eagle	H	24	L	5.4	5.125	2,800	0.299‡	6.5	3,500	3,500	70*	2,600‖	3,300	9,000	100/130	3,900	1.11
													2,400‖	3,300	19,000			
Packard Motor Car Co....	V-1650 (Rolls-Royce)	V	12	L	5.4	6	1,649	0.47	6.5	2,200†	3,000	88*	......	.....	......	115/145	1,690	0.77
Wright Aeronautical Corporation	Cyclone 7	R	7	A	6⅛	6 5/16	1,301	0.563	6.2	800	2,600	45*	700	2,400	5,000	91/98	1,015	1.27
	Cyclone 9	R	9	A	6⅛	6⅞	1,823	0.563	6.8	1,525	2,800	57*	1,275‖	2,500	3,500	100/130	1,398	0.92
													1,125‖	2,500	10,600			
	Cyclone 18	2-R	18	A	6⅛	6 5/16	3,347	0.438	6.5	2,500	2,800	52*	2,000‖	2,400	4,800	100/130	2,780	1.11
													1,800‖	2,400	15,000			
Bristol Aeroplane Company, Limited	Hercules	2-R	14	A	5¾	6½	2,360	0.440	7.0	2,000	2,800	55	1,600	2,400	3,500	100/130	2,060	1 03
	Centaurus	2-R	18	A	5¾	7	3,270	0.400	7.2	3,000†	2,700	60	2,150	2,400	5,000	115/145	2,980	0.993
D Napier & Sons, Limited	Sabre	H	24	L	5	4¾	2,238	0.252	7.0	3,050†	3,850	65	2,820	3,850	12,500	115/145	2,560	0.837

* Estimated.

† Military ratings, with water injection and 115/145 fuel.

‡ Contrarotating propellers.

§ Numbers in excess of 100 are "performance numbers" (roughly ratio of power possible without knocking to that with 100 octane).

‖ Where two lines of figures are given for one engine, the upper line refers to performance in low supercharger gear ratio, the lower line to performance in high gear ratio.

partment. In addition, fire-extinguishing nozzles equipped to supply carbon dioxide or other fire-extinguishing material are located at strategic points in the engine nacelle. There is always a *fire wall*, or metal bulkhead, immediately behind the engine, for the purpose of shielding the airplane structure, tanks, etc., from an engine-compartment fire.

Complete Engine Installation

Figure 98 shows, diagrammatically, a complete installation for a small single-engine airplane with one fuel tank. To show a modern transport or military installation in a single diagram would be nearly impossible on account of its complexity. Even this diagram leaves out a number of important details such as electric wiring, hot-air intake, exhaust manifold, and control rods or cables.

CHAPTER VIII

THE GAS TURBINE: THE TURBOPROP ENGINE, THE TURBOJET ENGINE; RAMJET AND ROCKET ENGINES

It was not until the latter part of the Second World War that any power plant other than the reciprocating engine came to be recognized as practicable for aircraft propulsion. Now it can be said, however, that all the types which are the subject of this chapter are recognized as being useful for aircraft propulsion, each within its own special field.

THE GAS TURBINE

The basic power-producing element of both turboprop and turbojet engines is a *gas* turbine. The principal elements of a gas turbine are (1) the *compressor*, which compresses air and delivers it to (2), the *combustion chambers*, where fuel is sprayed in and burned, thus raising the temperature of the gases. From the combustion chambers, hot gases flow to (3), the *turbine*, which is mounted on the same shaft as the compressor. The turbine is driven by streams of hot gas which flow through the turbine nozzles at very high velocity as they expand from combustion chamber pressure down to atmospheric pressure.

If the turbine power exceeds the power required to drive the compressor and auxiliaries, the excess power is delivered through gears to a propeller. This complete arrangement is called a *turboprop engine.* If, on the other hand, the turbine is designed to give only enough power to drive the compressor, no propeller and no gears are installed and the arrangement is called a *turbojet engine.* In such engines the entire thrust is due to the stream of hot exhaust gases issuing from the *exhaust nozzle.*

Since the turboprop engine is perhaps easier to understand than the turbojet engine, it will be described in detail first.

THE TURBOPROP ENGINE

A typical turboprop engine is illustrated diagrammatically in Fig. 99.

The **compressor** is usually of the *axial* type, as illustrated. This type of compressor consists essentially of a series of carefully designed fans, all mounted on the same shaft, one behind the other. The first

"fan" consists of a circular row of rotating blades which deliver air to a set of stationary blades attached to the casing. These blades redirect the air into the next set of revolving blades, which, in turn, deliver to another set of stationary blades, and so on through the compressor. Each set of rotating and stationary blades is called a *stage*, and such compressors usually have from 10 to 14 stages. The velocity imparted to the air by the rotating blades of each stage is partly converted into pressure in each stage. The pressure ratio of the compressor is the product of the *pressure ratio* of each stage, pressure ratio being defined

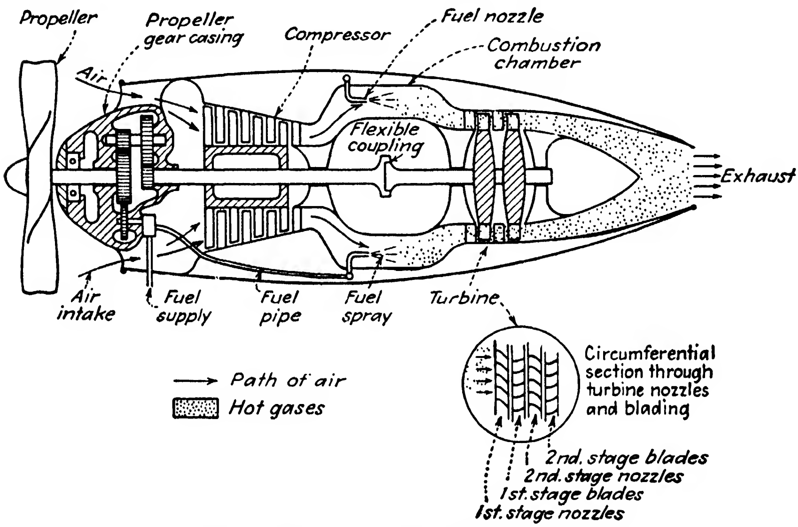


FIG. 99. Turboprop engine diagrammatic section.

as the ratio of absolute delivery pressure to absolute inlet pressure. As shown in the figure, the blades of successive stages get shorter, because as the air is compressed, its specific volume decreases, and the area required for flow at a given velocity is reduced.

Combustion Chamber. The compressor delivers air to one or more combustion chambers. These usually consist of cylindrical tubes placed around the circumference of the engine with their axes roughly parallel to the main-shaft axis (see Figs. 100 and 103). Fuel is sprayed in near the upstream end of each chamber. The chambers have various baffle arrangements to prevent the flame from "blowing out," and they usually have an inner perforated shell (see Figs. 103 and 104) located just inside the outer shell. Air from the compressor circulates between the two shells, thus protecting the outer shell from the very

high flame temperature. The fuel spray is ignited by a spark in starting, but burns continuously thereafter.

The combustion chamber is one of the features of the gas turbine which has required considerable development. At the fuel jet, the air velocity must be very low in order not to blow out the flame. In order to secure the necessary low velocity, the total cross-sectional area of the combustion chambers is large compared to the area of the compressor exit or turbine nozzles. Furthermore, various *baffles* and *screens* are placed in the combustion chamber in order to secure good "flame stabilization," *i.e.*, freedom from blowout under all flight conditions.

As will be seen in Figs. 103 and 104, combustion chambers are usually arranged so that only part of the air is fed into the immediate vicinity of the fuel jet, the rest of the air mixing with the combustion air downstream from the burner. Combustion chambers are worked out chiefly by trial, the chief criteria of good design being resistance to blowout, especially at high altitudes, and small pressure loss.

Turbine. The turbine is similar in design and construction to the exhaust turbine described in Chap. VI (see Fig. 78). In turboprop engines, the turbine is more often in two stages (Figs. 99 and 101) than in one stage (Fig. 103). The turbine is usually mounted on essentially the same shaft as the compressor, although there is often a flexible coupling in the shaft to allow for misalignment. The turbine, of course, furnishes the power to drive the compressor. Power in excess of that needed for driving the compressor is delivered to a propeller reduction gear, usually located at the compressor end, shown in Figs. 99, 100, and 101.

At first glance it is difficult to see that the turbine can be made to have more power than that required to drive the compressor, since the pressure drop from combustion chamber to atmosphere cannot be greater than the rise in pressure furnished by the compressor. The explanation is to be found in the great increase in *volume* of the gases caused by the temperature increase associated with combustion of the fuel. A large volume of gas falling through a certain range in pressure can do more work than is required to compress a smaller volume through the same pressure range. Hence excess power can be obtained from the turbine.

It is evident that the process through which the gases go in the gas turbine is closely related to the corresponding process in a reciprocating engine. A given element of the gas is compressed, then its temperature is increased by combustion, after which it is expanded. The

essential difference is that the combustion process increases the *volume* at (nearly) *constant pressure* rather than the *pressure* at (nearly) *constant volume.*

Exhaust System. The exhaust gases from the turbine are discharged through a large *exhaust nozzle* pointing to the rear. Discharge of the gases rearward furnishes considerable *thrust* in addition to that furnished by the propeller. This exhaust thrust is provided (1) because a turbine designed to use *all* the pressure drop between combustion chambers and atmosphere would be much larger than those ordinarily used, and (2) because, except at very low flight speeds, the over-all propulsive efficiency is higher when part of the pressure drop is used in the jet. In turboprop engines now under development, the ratio at take-off of jet thrust in pounds to shaft horsepower is from 0.20 to 0.30.

Starting. Starting of turboprop engines is accomplished, as with reciprocating engines, by rotating them by means of an electric starter. Relatively powerful starters are required because the starting speed required is about 10 per cent of the rated speed. The ignition sparks must be functioning during the starting process only.

Compound Turbines. It is possible to increase the efficiency of gas turbines, particularly at part load, by using various combinations of two or more turbines and compressors (see Ref. E19). The use of intercoolers between compressor stages, burners between turbine stages, etc., can also effect improvements in efficiency. However, such devices usually increase the weight and bulk of the power plant, and do not seem appropriate for airplane use, at least at the present time.

Materials. Combustion-chamber parts, as well as turbine nozzles, turbine blades and wheels, and jet nozzles must be made of stainless-type steels, which do not easily oxidize at high temperatures. Shafts and gears are of alloy steel as in reciprocating engines. Compressor and gear casings are made of aluminum or magnesium castings, and the compressor rotor and blades are usually of forged aluminum.

Lubrication. Lubrication of main shaft and auxiliary bearings is usually accomplished by circulating oil from a tank to these bearings and back again by means of pumps driven by gears from the main shaft. The mechanical friction of gas turbines is relatively small because the bearings are few in number, and there is nothing corresponding to the piston friction of a reciprocating engine. Gas friction in blower and turbine is accounted for in measuring the efficiencies of these units.

Oil consumption of gas turbines should be small, since there are no lubricated parts, such as the piston and cylinder walls of a reciprocating engine, which are exposed to the flow of hot gases.

Auxiliaries. Auxiliaries required by a gas turbine, either with or without propellers, are driven by means of gears from the main shaft. These auxiliaries include fuel pumps, oil pumps, electric generator, and tachometer. Starting is accomplished, as in the case of a reciprocating engine, by an electric motor, battery-supplied. A suitable starter mounting geared to the main shaft must, of course, be provided.

Control of Turboprop Engines. The airflow through a turboprop (or turbojet) engine is not regulated by a throttle as in a reciprocating engine. Instead, control of output is obtained by regulating the fuel flow only. Although there is a high limit on fuel-air ratio set by the combustion-temperature limit, there is no fixed low limit, as in the case of a reciprocating engine. Thus, output can be controlled by controlling fuel-air ratio only, and the pilot's throttle is essentially a fuel-air-ratio device rather than an inlet-density device, as in the case of the reciprocating engine. For protection of the engine, automatic devices are usually added which limit fuel flow whenever the maximum allowable shaft speed or combustion temperature is reached. There is usually, also, an automatic control connection between the propeller governor (see Chap. X) and the fuel-flow control so that the appropriate propeller speed will be used for each setting of the power control.

TYPICAL TURBOPROP ENGINES

General Electric TG-100B

Figure 100 shows the General Electric TG-100B turboprop engine. This engine is rated at 1,900 hp at 13,000 rpm for take-off, with an additional 500-lb thrust from the exhaust.

The engine has a 14-stage axial compressor, which receives air from an annular air intake located behind the propeller and compresses it through a ratio of 5.5 before delivering it to the nine cylindrical combustion chambers. In each of these fuel is sprayed in and burned and the hot gases flow through a single-stage turbine to the exhaust nozzle.

The propeller gearbox is located at the compressor end of the engine just ahead of the annular air intake. The ratio of turbine shaft speed to propeller shaft speed is 11.35. The gear is of the planetary type (see Fig. 82).

Bearings. The compressor-turbine shaft is mounted on ball bearings. There is a splined joint between turbine and compressor to allow for misalignment.

Lubrication. Oil is supplied to bearings and gears by means of engine-driven pumps connected to an external tank. Scavenging pumps remove excess oil from the gear case and the main-shaft housing and return it to the external tank.

Turbine Cooling. Bearings and turbine wheels must be air-cooled in turboprop engines. This is usually accomplished, as in this engine, by bleeding off a small fraction of air from the compressor outlet, and arranging ducts to guide it over the shaft bearings and to the front

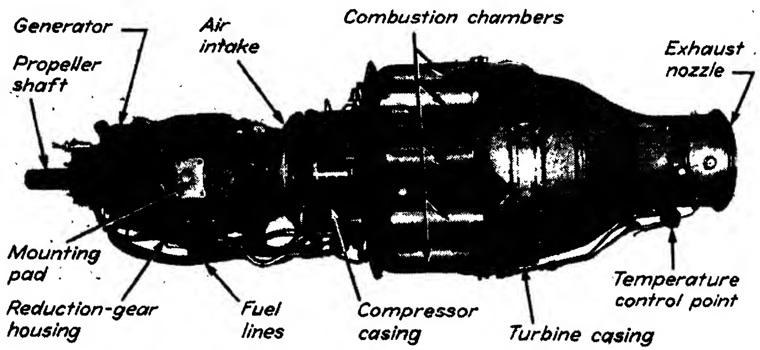


FIG. 100. General Electric TG-100B turboprop engine. (*General Electric Company.*)

and rear faces of the turbine rotor. At the rotor, air flows outward from near the center and joins the stream of hot gases flowing through the blades.

Auxiliaries. This engine carries gear-driven fuel and oil pumps, generator, and control equipment mounted on the propeller gear housing. Starting is by means of an electric motor geared to the shaft through a one-way clutch. This engine has undergone extensive flight tests, but is not yet in general service use. Its over-all dimensions and weight are given in Table 5.

ARMSTRONG SIDDELEY MAMBA

Figure 101 shows the Armstrong-Siddeley Mamba (British) turboprop engine. This engine is rated at 1,020 hp plus 325 lb jet thrust at sea level, 15,000 rpm. It is quite similar to the General Electric TG-100 engine previously described with the following exceptions.

Compressor has 10 stages.
Turbine has 2 stages.
Turbine-propeller gear ratio is 10.35.
There are 6 combustion chambers.

Accessories are carried on the blower casing instead of on the gear housing. (A shaft to drive remote accessories is also provided.)

Cooling. Air is bled from the compressor outlet into the turbine-shaft casing, from which it flows into the large hollow turbine shaft. From the hollow turbine shaft, air flows out through holes placed so as to feed the air outward along the faces of the turbine wheels and into the stream of hot gases passing through the turbine blades.

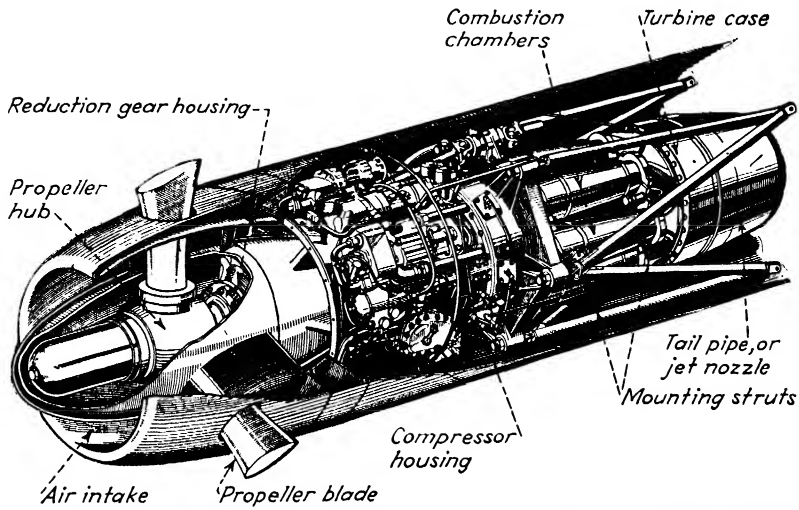


FIG. 101. Armstrong-Siddeley Mamba turboprop engine. (*Armstrong-Siddeley Motors, Ltd.*)

THE TURBOJET ENGINE

The turbojet engine is basically like the turboprop engine except that the turbine is designed to give only enough power to drive the compressor. In this case the gases issue from the turbine with very high velocity. By projecting this stream of gas backward from the airplane, a driving thrust is produced which acts in the same way as the thrust produced by the air which a propeller drives rearward (see Chap. X).

Control of Turbojet Engines. As in gas turbines, the control of turbojet engine output is by means of fuel flow only. Automatic controls to limit rotor speed and combustion temperature may be added, as in the case of turboprop engines. The turbojet engine has the simplest control mechanism of any of the three principal types of engine, since it has no propeller controls.

Rating of Turbojet Engines. This type of engine is usually rated on the basis of maximum *static sea-level thrust*, *i.e.*, the maximum thrust at standard sea-level conditions at no forward speed. The thrust in flight is usually less than the static thrust and varies with speed, altitude, and load, as explained in Chap. IX.

TYPICAL TURBOJET ENGINES

Westinghouse 19XB2B

Figure 102 is a cutaway view of the Westinghouse 19XB2B turbojet engine, rated at 1,600 lb static thrust at 17,000 rpm. This engine resembles the turboprop engines previously described except, of course, that it has no propeller shaft or reduction gear.

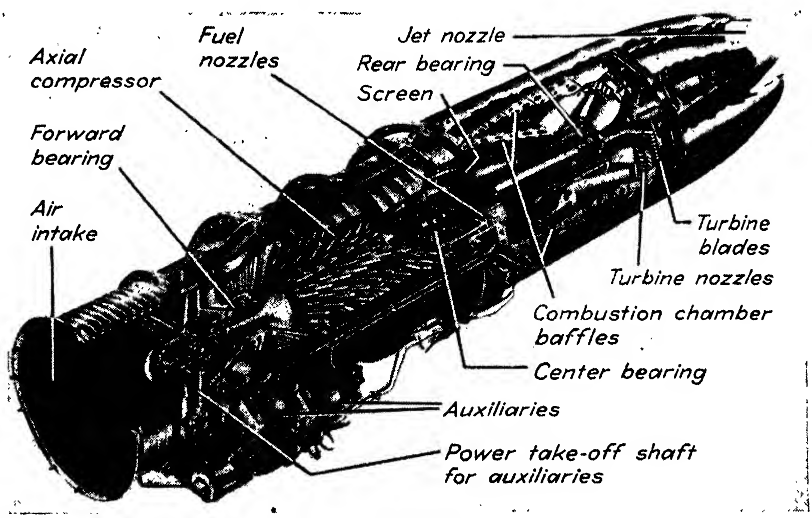


Fig. 102. Westinghouse 19XB2B turbojet engine, cutaway view. (*Westinghouse Electric Corporation.*)

An unusual feature of this engine is the use of one annular combustion chamber instead of several cylindrical ones. This combustion chamber surrounds the shaft housing between compressor and turbine and has a number of fuel nozzles located around its periphery at its upstream end.

Auxiliaries include starter, generator, ignitor, speed governor, and tachometer drive, as well as fuel and oil pumps.

General Electric TG-180

Figure 103 shows the General Electric TG-180 turbojet engine which is now extensively used in United States fighter airplanes. This

engine is rated at 4,125 lb static thrust at 7,700 rpm for take-off. Except for the absence of the propeller gearing, it is quite similar in detail design and construction to the TG-100B turboprop engine previously described.

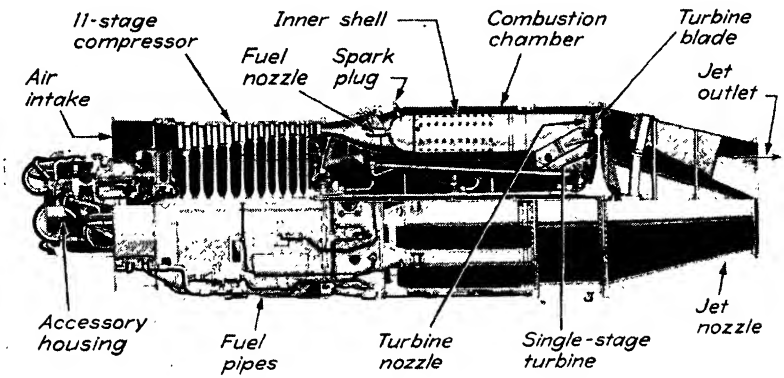


FIG. 103. General Electric TG-180 turbojet engine (sectional view). (*General Electric Company.*)

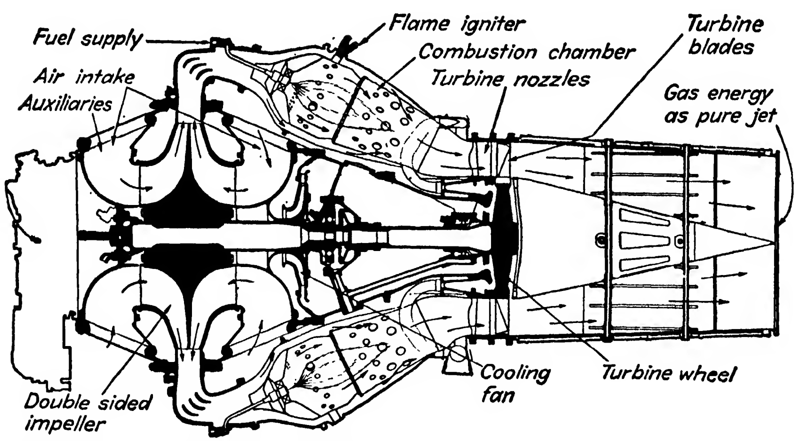


FIG. 104. Rolls-Royce Nene turbojet engine, diagrammatic cross section. (*Taylor Turbine Corporation.*)

Rolls-Royce Nene

Figure 104 is a diagrammatic cross section and Fig. 105 a view of the Rolls-Royce Nene turbojet engine rated at 5,000 lb static thrust at 12,300 rpm. This engine, unlike those previously described, is equipped with a *centrifugal* compressor.

The centrifugal compressor is similar in design and construction to those previously described in connection with superchargers for reciprocating engines (see pages 89 and 92). In this case, however, the compressor is of the *double-entry* type. The rotor is essentially two convential rotors placed "back to back" and delivering into a common diffuser. The compressor delivers air at about 3.5 times inlet pressure to 12 cylindrical combustion chambers. The arrangement of nozzles and baffles in these chambers is shown in the cross section.

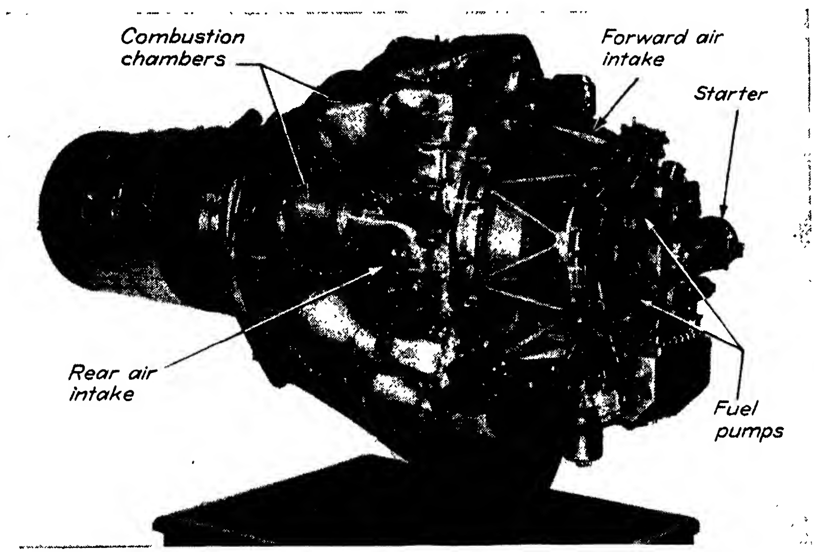


FIG. 105. Rolls-Royce Nene turbojet engine. (*Taylor Turbine Corporation.*)

The combustion chambers feed into an annular *nozzle box*, which carries the nozzles. The main shaft has three bearings—a center ball bearing with roller bearings at the front of the compressor and turbine.

An unusual feature of the Nene is a small centrifugal cooling blower, or fan, mounted on the main shaft just behind the main compressor. This blower delivers air to the upstream face of the turbine wheel. The cooling air flows radially outward along the face of the turbine wheel and is finally collected in an annular space just under the nozzles and discharged to the atmosphere, through a system of pipes passing between the combustion chambers.

The usual auxiliaries are mounted just in front of the compressor. As indicated in Table 5, this engine has an unusually small weight per pound thrust.

TABLE 5. REPRESENTATIVE TURBOPROPELLER AND TURBOJET AIRCRAFT ENGINES

Manufacturer	Model	Country	Prop. or jet	Sea-level static rating			Specific fuel consumption*	Propeller gear ratio	Compressor		Turbine, number of stages	Overall dimensions		Weight		Max. area, cross section, sq ft	Thrust, lb/sq ft cross section
				Thrust, lb	Shaft, hp	Rpm			Type	Number of stages		Max. diameter, in.	Max. length, in.	Lb	Lb/lb thrust		
General Electric Company....	I-40	U.S.	J	4,000	...	11,500	1.185	...	Cent.	1	1	48	102	1,820	0.455	12.6	318
	TG-180	U.S.	J	4,125	.	7,700	1.026	.	Axial	11	1	36¾	166	2,450	0.595	7.4	557
	TG-100B	U.S.	P+J	500	1,900	13,000	0.61†	0.088	Axial	14	1	35⅛	114⅝	1,984	0.83†	6.8	352
Westinghouse Electric Corp ...	X19B	U.S.	J	1,368	...	18,000	1.28	.....	Axial	6	1	26	90	809	0.590	3.7	370
	X19XB2B	U.S.	J	1,600	..	17,000	1.15	.....	Axial	10	1	19	94	718	0.450	2.0	800
Armstrong Siddeley Motors, Limited	Python SP-2	G.B.	P+J	1,150	3,670	8,000	0.63†	.....	Axial	14	2	48	102	2,980	0.60†	12.6	383
	Mamba	G.B.	P+J	325	1,020	15,000	0.63†	0.097	Axial	10	2	30	.....	760	0.565†	4.9	275
Bristol Aeroplane Company, Limited	Theseus	G.B.	P+J	500	1,950	9,000	.....	.....	Comb.‡	1 cent. 8 axial	3	48	112	2,310	0.94†	12.6	195
De Havilland Aircraft Company, Limited.	Ghost	G.B.	J	5,000	.....	10,000	1.06	.....	Cent.	1	1	53	116	2,011	0.40	15.3	325
Rolls-Royce, Limited....	Nene	G.B.	J	5,000	....	12,300	.....	.....	Cent.	1	1	50	97	1,600	0.32	13.7	365
	Clyde	G.B.	P+J	1,225	3,020	6,000	.....	.....	Comb.‡	1 cent. 9 axial	2	47	121	2,800	0.66†	12.0	353

* Pounds per hour per pound thrust at cruise except where otherwise noted.

† Based on propeller horsepower, plus jet thrust horsepower at 375 mph cruise.

‡ Combined: First stage centrifugal, subsequent stages axial.

RAMJET ENGINES

In turbojet engines operating at present airplane speeds, a small part of the work of compression is accomplished by accelerating the inlet air to airplane speed. The dynamic pressure q available from this acceleration has already been discussed (see page 17). Jet engines have been built in which the dynamic pressure alone served for compression. The outstanding example of this type of jet engine was that used on the German V-1 flying bomb. The engine (Fig. 106*a*) is very simple, consisting of a long tube with lightweight nonreturn valves near the forward end. In flight the dynamic pressure opens

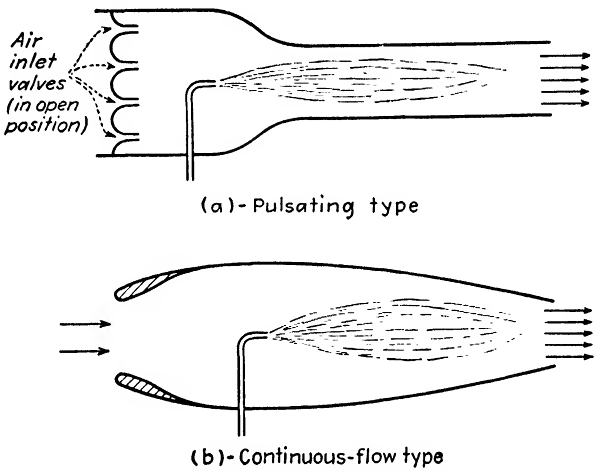


FIG. 106. Ram jets, (*a*) pulsating type, (*b*) continuous-flow type.

these valves, allowing air to flow through the tube. Fuel is supplied through a nozzle as shown, and is ignited by a spark to start with and later by flame left over from the previous "cycle." When the fuel-air ratio reaches an ignitable value, the mixture of fuel and air so formed explodes. The explosion creates a considerable pressure in the tube, which closes the nonreturn valves and ejects gas at high velocity out the rear end of the tube, thus furnishing thrust. The flow of gases out of the nozzle reduces the pressure in the tube to the point where the one-way valves again open and the cycle starts over again. The rapid repetition of this cycle is responsible for the noise from which the name "buzz bomb" was derived. This type of engine is called a *pulsating ramjet* engine. It is very inefficient, *i.e.*, the fuel consumption per pound thrust per hour is very high. However, it is extremely cheap to manufacture and was therefore well suited to the compar-

atively short range (150 to 200 miles) over which it was used. This type of engine does not appear promising for use in man-carrying airplanes.

The *steady-flow* ramjet engine should also be mentioned here, although its probable field of usefulness appears to be limited to very high speed missiles and possibly helicopters. This ramjet is similar in construction to the pulsating ramjet, except that the tube has a different shape (Fig. 106*b*) and the nonreturn valves are omitted. If the speed is high enough, this device will produce thrust in the same manner as thrust is produced by a turbojet engine. Air compression is entirely due to forward velocity, so that no turbine is required. Engines of this type are still highly experimental, and no ramjets with efficiencies comparable to those of a turbojet engine have yet been announced.

ROCKETS

The rocket is a form of jet engine in which thrust is created by chemical reaction between two or more substances, all of which are carried in the aircraft. The *propellant* of a rocket is taken as including all the reacting substances.

The simplest form of rocket (Fig. 107*a*), uses a solid propellant similar to a slow-burning gunpowder. Combustion of this substance, usually initiated by an electric spark, generates large volumes of gas very rapidly. The flow of gas from the nozzle at the rear of the rocket produces thrust, as in a turbojet engine.

Another form of rocket uses two liquids stored in separate tanks. To operate the rocket, these liquids are fed into a combustion chamber, where they are ignited and thereafter continue to burn as long as the supply continues. Propellant feed may be accomplished by gas pressure in the tanks (Fig. 107*b*) or from pumps driven by a small turbine (Fig. 107*c*), which operates by combustion of a small fraction of the main propellant, or from a separate supply of its own. The German V-2 bomb was powered by a rocket of the latter type.

Use of Rockets. The propellant consumption of rockets is too high to make them of interest for anything but very short-time use. On the other hand, rockets can generate enormous thrust for short periods, in proportion to their weight and size. For example, the German V-2, weighing 27,500 lb at take-off, produced a thrust of 60,000 lb for about 1 min, and the thrust power just before the fuel ran out was 600,000 hp (see Ref. E15)!

Rockets are already used to assist the take-off of military airplanes

and at least one fighter plane, the German Messerschmitt Me-163 (Ref. E14), used during the Second World War, was powered by a liquid-fuel rocket engine. This airplane was used as an interceptor fighter, and could climb to 30,000 ft in 2½ min, which nearly exhausted

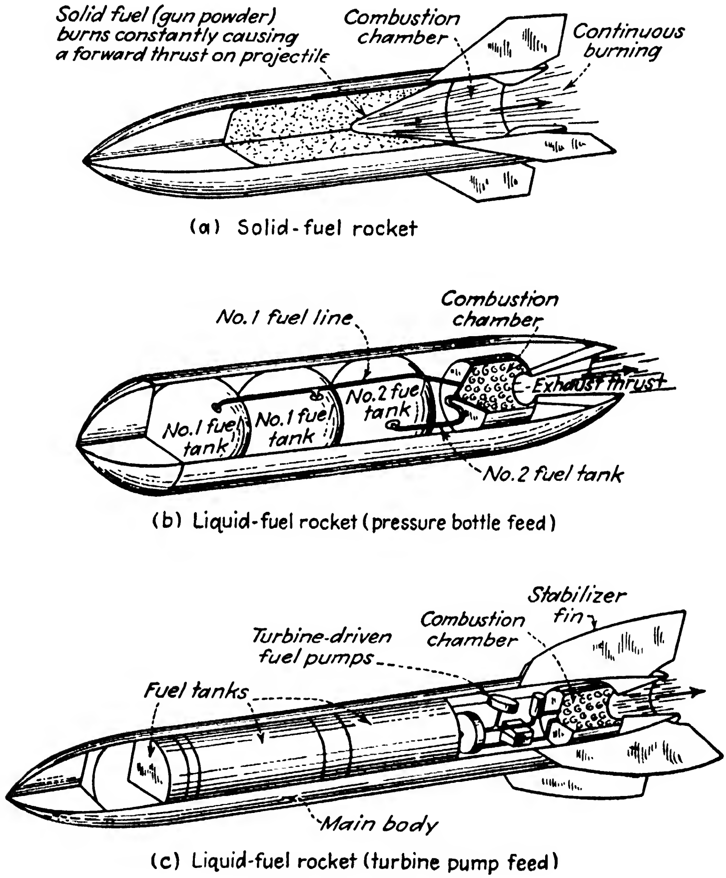


FIG. 107. Rocket types.

its fuel supply. It was expected to do its fighting on the way back to earth, and the small amount of fuel which remained after climb was used in short bursts of speed, as required. The propellant used was hydrogen peroxide and gasoline.

CHAPTER IX

ELEMENTARY ENGINE THEORY, ENGINE PERFORMANCE, COMPARISON OF ENGINE TYPES

Definitions. In order to deal with problems in engine performance and to compare different kinds of engines, scientific methods of measuring engine performance are necessary. A discussion of this subject requires the use of some common terms in their specialized scientific sense; therefore a few definitions of such terms will follow. These definitions can be found in any engineering textbook, but they are given here for the sake of emphasis, and for the convenience of those readers to whom the use of such terms is not entirely familiar.

Work. Work, for scientific purposes, is defined as the product of a force and the distance through which it acts. For example, a man or machine that lifts a weight of 5 lb through a distance of 5 ft has done 25 ft-lb of work. As another example, if the gases in the cylinder of a reciprocating engine exert an average force on the piston of 1,000 lb while the piston moves 6 in., the work done on the piston by the gases is $1{,}000 \times \frac{1}{2} = 500$ ft-lb. We shall use as the unit of work the *foot-pound*, and the symbol w.

Power. By means of a block and tackle or a system of levers, a child or a small engine could do the same total amount of mechanical work as a man or a large engine, although a longer time would be necessary for the process. To define the ability of a man or an engine, therefore, time must also be taken into consideration. *Power* is work per unit of time, and through customary usage the unit of power is called a *horsepower*.

Horsepower. The term *horsepower* as used in engineering has very little relation to the power developed by a horse. It is defined as the power necessary to lift a load of 33,000 lb through a height of 1 ft in 1 min. A large horse can do this amount of work for a short time but cannot keep it up continuously. A man can develop only about $\frac{1}{10}$ hp for any extended period of time. We will use the symbol hp for horsepower.

If the foot-pounds of work done by an engine are divided by the number of minutes required to do the work and by 33,000, the horsepower developed will be obtained. Expressed as a formula, this

becomes

$$\text{hp} = \frac{w}{33{,}000 \times t} \tag{1}$$

where t is the minutes of time taken to do the work w foot-pounds. If we have means for measuring the average force exerted and the distance through which that force is applied in a given number of minutes, we can compute horsepower. In the case of the previous example, if the time required for the piston stroke was $\frac{1}{60}$ sec or $\frac{1}{3600}$ min, the power being developed by the gases pushing the piston was

$$\frac{500}{\frac{1}{3600} \times 33{,}000} = 54.5 \text{ hp}$$

Torque. Work can be done in turning a shaft as well as in applying a force. The force required to turn a shaft depends on the length of the lever arm used. If a force of f pounds is used at the end of an arm l feet in length to turn a shaft through one revolution, the work done is force times distance as before, but the distance is $2\pi l$ feet and the work is, therefore, $2\pi lf$ foot-pounds. The product of the force and the lever arm, fl, is called *torque*, for which the symbol (T) will be used. When an engine turns a shaft, the work done in 1 min is $2\pi(T)N$ foot-pounds, where N is the rpm, and the *shaft horsepower* can be obtained from the relation

$$\text{shp} = \frac{2\pi(T)N}{33{,}000} \tag{2}$$

The shaft horsepower is often called the *brake* horsepower because it can be measured by an instrument called a "brake"; bhp is the usual abbreviation for brake horsepower.

As an example of the use of Eq. (2) suppose an engine produces 5,000 ft-lb of torque at 2,000 rpm. The power will be

$$\frac{2\pi \times 5{,}000 \times 2{,}000}{33{,}000} = 1{,}900 \text{ bhp}$$

Specific Fuel Consumption. Next to the power output, the item of performance which is of most interest in an airplane engine is its fuel consumption.

Obviously, a high-powered engine will consume more fuel in a given time than an engine of less power, other things being equal, and therefore the fuel consumption must be related to the power output in order to be of real significance. The specific fuel consumption is usually expressed in terms of pounds of fuel used per hour divided by the brake

horsepower of the engine. However, in the case of airplanes the net *thrust* of the propulsive system is usually of more interest than the brake horsepower, so that *thrust specific fuel consumption* is often used. This quantity will be discussed in the final section of this chapter.

Efficiency. The specific fuel consumption of an engine depends on the *heat of combustion* of the fuel used and the *efficiency* of the engine. In order to define these terms, it is necessary to discuss what is called *heat* in scientific language.

Heat. Heat is the form of energy which flows from one body to another because the temperature of the first body is higher than the temperature of the second one. When a fuel is burned with air or with oxygen, the resultant temperature of the burned gases is very high, and heat will flow from the gases to any cooler substance with which they come in contact.

The *heat of combustion* of a fuel is the quantity of heat given off by the process of burning a unit weight of fuel with an excess of oxygen and cooling the resulting hot gases back to their original temperature. Petroleum fuels all have heats of combustion in the neighborhood of 20,000 Btu per lb. The British thermal unit of heat is that quantity of heat required to raise the temperature of 1 lb of water through 1°F, and the usual symbol for this quantity is Btu.

Heat and Work. It has long been known that mechanical work may be converted into heat and that a given quantity of heat is equivalent to a certain amount of mechanical work, although the whole quantity of heat can never be converted into work. In other words, heat and work are theoretically interchangeable and bear a fixed relation to each other. This relation is 778 ft-lb of work per Btu. Thus, if the heat of combustion of 1 lb of petroleum fuel could all be converted into mechanical work, $778 \times 20{,}000 = 15{,}560{,}000$ ft-lb of work would result!

Actually, for reasons too involved to discuss here, no engine can convert more than about 45 per cent of the heat of combustion of its fuel into work, and most engines do not do nearly as well as that figure.

At this point, it is convenient to define absolute temperature and absolute pressure. On the Fahrenheit scale generally used in the United States, absolute temperature is equal to Fahrenheit temperature plus 460 degrees. This temperature will be designated by θ, the Greek letter *theta*. Absolute pressure is the pressure measured by an ordinary pressure gage, plus the atmospheric pressure (see Fig. 6). In referring to pressure in this chapter, absolute pressure in pounds per square inch will be designated by the letter p.

Thermal Efficiency. This is the term used to evaluate the effectiveness of an engine in converting the heat of combustion of its fuel into mechanical work.

Since the work done by an engine in 1 min is bhp $\times$ 33,000 ft-lb, the definition of thermal efficiency E can be expressed algebraically as follows:

$$E = \frac{\text{bhp} \times 33{,}000}{778 Q_c M_f} = \frac{\text{bhp} \times 42.4}{Q_c M_f} \tag{3}$$

where Q_c = heat of combustion of the fuel, Btu per lb

M_f = fuel supplied to the engine, lb per min

As an illustration of the use of expression (3), if the engine in the example on page 142 uses 20 lb of fuel per minute, its efficiency is

$$\frac{1{,}900 \times 42.4}{20{,}000 \times 20} = 0.202$$

Relation of Thermal Efficiency and Specific Fuel Consumption. Rearranging expression (3) gives

$$\frac{M_f}{\text{bhp}} = \frac{42.4}{EQ_c} \tag{4}$$

The quantity 60 M_f/bhp is, by definition, the *specific fuel consumption,* abbreviated sfc. From (4)

$$\text{sfc} = \frac{60 M_f}{\text{bhp}} = \frac{2{,}445}{EQ_c} \tag{5}$$

which shows that specific fuel consumption, with a given fuel, is inversely proportional to thermal efficiency.

Importance of High Thermal Efficiency. If two engines use equal amounts of fuel, obviously the engine which converts into work the greater part of the energy in the fuel, *i.e.*, which has the higher thermal efficiency, will deliver the greater amount of power. Furthermore, the engine which has the higher thermal efficiency will have lower exhaust temperatures because more of the heat of combustion of the fuel will be converted into work. Low exhaust temperatures are desirable from the point of view of exhaust-valve durability. Lastly, a high thermal efficiency means a low specific fuel consumption, and therefore requires less fuel for a flight of a given distance at a given power. The practical importance of high thermal efficiency is therefore threefold, and it constitutes one of the most desirable features in the performance of an airplane engine.

Fuel-air Ratio. The fuel-air ratio for satisfactory performance varies with the type of engine and with its regime of operation. For the petroleum fuels generally used, the fuel-air ratios given by Table 6 may be taken as good practice.

TABLE 6

Engine type	Regime of operation	Fuel-air ratio	
		By weight	By volume*
Reciprocating	Take-off, "dry"	0.10–0.12	0.025–0.03
	Take-off with water injection	0.08	0.02
	Cruising	0.06–0.08	0.015–0.02
	Idling	0.07–0.09	0.018–0.023
Turbojet or turboprop	Take-off	0.017–0.02	0.004–0.005
	Take-off with water injection	0.025	0.006
	Cruising	0.014–0.017	0.0035–0.004
	Idling	0.010 or less	0.0025 or less

* Based on volume of the vaporized fuel to volume of air at standard sea-level conditions, namely, 14.7 lb per sq in. pressure and 60°F temperature.

From this table it will be seen that the largest fuel-air ratio ever used is about one pound of fuel to every eight pounds of air. At this ratio at sea level, the volume of the vaporized fuel is about 3 per cent of the volume of the air which goes with it. Furthermore, the volume of the fuel before vaporization is about 150 times smaller than the volume of the fuel vapor.

The above figures are given to emphasize the fact that air capacity rather than fuel capacity dictates the size of internal-combustion engines. The fuel weight and volume are, of course, of utmost importance from the point of view of tank capacity, airplane weight, range of operation, etc. But from the point of view of the engine, the fuel it uses is the merest trickle compared to the tremendous volume of air it must "swallow" in a given time. Take, for instance, the example given on page 142, of a 1,900-hp engine using 20 lb of fuel per minute. If this were a reciprocating aircraft engine operating under best cruising conditions, the fuel-air ratio would be about 0.06, and the air consumption would be $20/0.06 = 330$ lb per min. Twenty pounds of liquid fuel would occupy less than half a cubic foot, while 330 lb of air at sea level would occupy 4,300 cu ft! At 20,000 ft the volume of air would increase to 7,900 cu ft per min or about 18,000 times the volume

of the liquid fuel! This example applies to a reciprocating engine. In the case of turbojet and turboprop engines, the air-to-fuel volume ratios are four or five times greater.

General Power Equation. If we let M_a be the pounds of air used per minute by an engine, and F be the fuel-air ratio, the pounds of fuel used per minute will be FM_a. Substituting this in Eq. (4) and rearranging gives

$$\text{bhp} = \frac{FM_aEQ_c}{42.4} \qquad (6)$$

which expresses the power of any internal-combustion engine in terms of its air consumption, fuel-air ratio, and thermal efficiency, using a fuel whose heat of combustion is known. This equation will be used later in explaining the performance of the various types of airplane engines.

PERFORMANCE OF THE RECIPROCATING ENGINE

In order to examine the performance characteristics of the reciprocating engine, it is necessary to examine in some detail the process which goes on inside its cylinder. Figure 108 is a plot of cylinder pressure vs. piston position or cylinder volume, and is called an *indicator diagram* because it can be obtained from an engine by means of an instrument called an *indicator* (see Ref. E7).

The dash lines in Fig. 108 represent the process for an *ideal* engine, *i.e.*, one which makes the best possible use of the fuel-air mixture. In this case the inlet process starts at point 1 at top center, and as the piston moves to bottom center (to the right) on the intake stroke, fuel-air mixture is drawn in at the *inlet* pressure and temperature, *i.e.*, at the pressure and temperature existing in the inlet manifold.

At point 2 the inlet valve closes, and compression takes place (without heat losses in the ideal engine) as the piston moves to point 3, top center on the compression stroke. At this point the ideal engine would ignite and burn the fuel instantaneously, raising the cylinder pressure to point 4. The piston then moves outward, and the cylinder pressure falls on the expansion stroke to bottom center, point 5, where the exhaust valve suddenly opens and the pressure falls instantaneously to the exhaust-system pressure.

The ideal process illustrated in Fig. 108 is called a *constant-volume* cycle because the combustion process is assumed to take place at constant volume, *i.e.*, at the cylinder volume at top dead center.

The work done on the piston is equal to the average difference in pressure between lines 4–5 and 2–3 multiplied by the piston area and

piston stroke. That average pressure difference is called the *indicated mean effective pressure* and is usually given in pounds per square inch. Since the ideal engine has no friction, its power at a given crankshaft turning speed (rpm) is proportional to its indicated mean effective pressure.

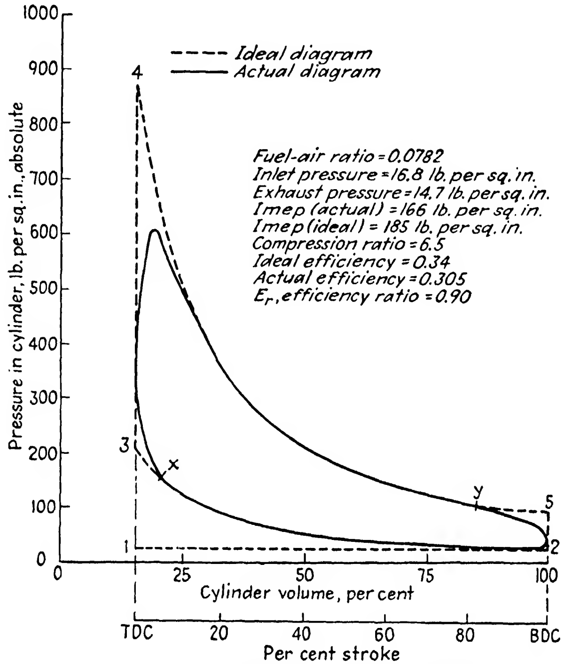


FIG. 108. Ideal and actual indicator diagrams. (Actual diagram from $6\frac{1}{8}$ by $6\frac{7}{8}$ aircraft engine operating at 1,710 rpm.) x = ignition point in actual diagram, y = exhaust valve opening point in actual diagram.

Efficiency of Reciprocating Engines. By means of present knowledge in the fields of chemistry and heat, it is possible to calculate the efficiency of the ideal process illustrated in Fig. 108. Figure 109 shows efficiencies of the ideal constant-volume cycle as a function of fuel-air ratio and compression ratio. The fuel is assumed to be gasoline. Such curves can be used to establish the best performance attainable by a reciprocating internal-combustion engine using a given fuel.

It is evident that the efficiency of the ideal cycle increases with increasing compression ratio and with decreasing fuel-air ratio. However, if we know that a certain real engine must be operated at given values of these quantities, we can calculate the corresponding ideal effi-

ciency. As an example, let us assume a compression ratio of 7 and a fuel-air ratio of .08. From Fig. 109, $E = 0.34$ for the ideal engine.

Air Consumption of the Ideal Engine. Neglecting the volume occupied by the fuel vapor, which, as we have seen, is very small, the weight of air drawn into the cylinder will be equal to the inlet air density multiplied by the displaced volume of the piston. Thus, for an ideal four-

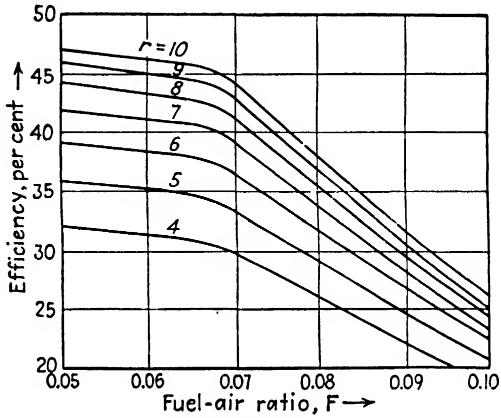


FIG. 109. Efficiency of ideal constant-volume cycle vs. compression ratio (r) and fuel-air ratio (F). (Fuel used is gasoline.)

cycle engine the air consumption would be

$$M_a = D \frac{N}{2} d_i \tag{7}$$

where M_a = weight of air per minute
D = displaced volume of all cylinders, cu ft
N = crankshaft rpm
d_i = density of air in inlet manifold (air density in pounds per cubic foot is equal to $2.71p/\theta$)

Power of the Ideal Engine. Combining Eq. (7) with Eq. (6) gives

$$\text{bhp}_i = \frac{DNd_i}{2} \frac{FQ_cE_i}{42.4} \tag{8}$$

where bhp_i is the horsepower of the ideal engine and E_i is its efficiency, which can be obtained from Fig. 109.

The Power of a Real Engine. This is always less than the power of an ideal engine of the same size running at the same fuel-air ratio, compression ratio, speed, and inlet density. The reasons for this difference are:

1. Efficiency of the actual cycle is lower than that of the ideal cycle.
2. The real engine has friction losses.
3. The air consumption of the real engine may be less than that of the ideal engine.

The full-line diagram in Fig. 108 was taken by means of an indicator (see Ref E7) from an engine having the same compression ratio and running under the same conditions as those chosen for the ideal diagram (dash lines). The following differences between the two diagrams are apparent:

1. On the compression stroke the pressure starts to rise rapidly after *ignition* at point x, which occurs before top center.
2. The pressure rise due to combustion is not instantaneous, but takes an appreciable time, and maximum pressure is reached after top center and is lower than that of the ideal cycle.
3. Pressure is lower than that of the ideal cycle after the exhaust valve opens, at y on the diagram.
4. Another difference between the real and ideal cycles is due to the heat loss, or flow of heat to the cylinder walls in the real engine. In the diagram shown in Fig. 108 the heat loss was apparently small, for otherwise the pressure during expansion would fall below that of the ideal cycle. Many real indicator diagrams show a small difference of this kind.

For the above reasons, the work done on the piston, and hence the indicated mean effective pressure is only 80 to 90 per cent of the work of an ideal cycle which starts with the same pressure and temperature at the beginning of the compression stroke and has the same compression ratio and fuel-air ratio.

Friction. The work done on the piston by the gases in an engine is called the *indicated work*. Part of the indicated work of a reciprocating engine is used to overcome piston and bearing friction and to overcome gas friction through the valves during the inlet and exhaust strokes. Some work, also, is used in driving the various auxiliaries such as oil pumps, supercharger, etc. For convenience, all the work which goes into these items will be called *friction* work, and the power so lost will be called *friction power*. The term *mechanical efficiency*, E_m, is defined as the ratio of shaft work to indicated work, or of brake horsepower to indicated horsepower. In well-designed engines operating at take-off or cruising conditions, mechanical efficiency is usually between 0.80 and 0.90.

Volumetric Efficiency. The real engine may consume somewhat less, or even a little more air than that indicated by Eq. (7) for the ideal

engine. The ratio of real-engine air consumption to that of the corresponding ideal engine is called the *volumetric efficiency.* Factors tending to reduce volumetric efficiency below 1.0 are heating of the fresh air by the hot engine parts as the air passes into the cylinder, and pressure drop due to friction through the inlet valve. The chief factor tending to increase volumetric efficiency above 1.00 is supercharging, *i.e.*, increasing the inlet pressure above the exhaust pressure. In practice, volumetric efficiencies range from 0.80 to 1.10, the higher values being characteristic of high ratios of inlet to exhaust pressure.

Reciprocating-engine Power Equation. From the foregoing discussion it is evident that we can express the power of a real reciprocating engine in terms of the power of the corresponding ideal engine multiplied by the following correction factors:

E_r = ratio between indicated work and ideal indicated work. This ratio is nearly constant over the useful operating range and may safely be taken as 0.85 for estimating purposes.

E_m = mechanical efficiency. Below critical altitude (see page 157) and at cruising power or above, E_m lies in the range 0.80 to 0.90. As the engine altitude increases above the critical altitude, mechanical efficiency decreases rapidly.

E_v = volumetric efficiency. As already stated this lies between 0.80 and 1.1, depending chiefly on crankshaft speed and on the ratio of inlet to exhaust pressure.

In algebraic terms the brake horsepower of a reciprocating engine can thus be expressed:

$$\text{bhp} = (\text{bhp of ideal engine})E_rE_mE_v$$

or

$$\text{bhp} = \left(\frac{DNd_i}{2}\right)\left(\frac{FQ_cE_i}{42.4}\right)E_rE_mE_v \tag{9}$$

This is an extremely important equation because it enables us both to explain and to predict how reciprocating engines will behave under various conditions of operation.

Limitations on Engine Power and Efficiency. Equation (9) might be taken to indicate that the power of an engine of a given size could be increased indefinitely by increasing the inlet density or by increasing the crankshaft speed, and Fig. 109 might be taken to indicate that efficiency could be increased indefinitely either by increasing the compression ratio or by reducing the fuel-air ratio. Actually there are definite limitations on each of these expedients, and these will now be discussed.

Limitations on Inlet Density. In unsupercharged engines, inlet density cannot exceed atmospheric density. This accounts for the well-known fact that the maximum power of such engines is greatest at sea level in cold weather and decreases with increasing altitude and increasing air temperature.

Supercharged engines, on the other hand, are usually equipped with superchargers which are capable of giving a very high inlet density at low altitudes. In such cases the inlet density is usually limited by *detonation*, as will be explained shortly. At low altitudes such engines must be throttled to a specified power or inlet-pressure limit.

Limitations on Compression Ratio. In real engines the choice of compression ratio is based on a number of interrelated factors including the relative importance of high output and low fuel consumption, the character of the fuel to be used, and design details. One of the most interesting of these limitations is that depending on the fuel and its tendency to detonate under conditions of high pressure and temperature in the cylinder.

Detonation. Figure 108 shows that the maximum pressure in an aircraft-engine cylinder may be very high. The corresponding maximum temperature is usually in the neighborhood of 4500°F. The real diagram of Fig. 108 was taken from a supercharged engine used for military and air-line purposes. The smaller engines used in private airplanes are unsupercharged and run with considerably lower cylinder pressures even at take-off, although the temperatures are nearly the same.

Referring again to Fig. 108, the combustion process starts at the point marked x where the mixture is ignited by a spark at two points[1] in the cylinder. From these points flame spreads through the gases until, at a point near peak pressure, the burning process is complete. While the time for the burning process is short in a high-speed engine (a matter of a few thousandths of a second), the flame front moves at a measurable velocity under normal conditions (see Refs. E4 and E5). Sometimes, on the other hand, the combustion process proceeds in this manner only for a certain time and then suddenly accelerates so that the last part of the gas to burn reacts with great suddenness. Under these conditions the indicator diagram will show violent fluctuations near the maximum-pressure point and a maximum pressure much higher than the normal maximum (see Ref. E5). In automobile engines this condition can be recognized by a sharp metallic *knock* or ringing sound, often heard when the engine is pulling very hard at low

[1] All modern aircraft engines use dual ignition with two spark plugs per cylinder.

speed. Severe detonation may cause overheating of spark plugs with consequent *preignition* and may even cause burning of valves, pistons, or cylinder heads. Since it is impossible to run with severe detonation for any great length of time, the highest pressures and temperatures which can be allowed in the cylinder must be lower than those at which severe detonation occurs.

Effect of Fuel on Detonation. The highest cylinder pressure which can be reached in a given engine without detonation depends to a great extent on the character of the fuel used. The tendency of gasoline to detonate in a given engine, under a given set of operating conditions, depends on its chemical composition and can be controlled to a great extent in the refining process. The detonation tendency of a fuel is measured by engine tests which compare its detonation characteristics with those of a mixture of two standard, or *reference*, fuels. These are pure hydrocarbons, one of which is known as normal *heptane* (C_7H_{16}), a severe "detonator," and the other *iso-octane* (C_8H_{18}), which has little tendency to detonate under ordinary engine conditions.

By mixing these two reference fuels in different proportions, different detonation characteristics can be obtained. The "octane number" of a fuel is equal to the percentage of iso-octane in normal heptane which has the same detonation characteristics in a standard engine test as the fuel in question. The higher the octane number, the less is the tendency to detonate, and, in general, the higher the cost of the fuel.

Antiknock Compounds. The tendency of a fuel to detonate can be controlled not only by the composition of the fuel itself, but also by the addition of very small quantities of certain chemicals called *antiknock compounds*. A chemical known as *tetraethyl lead*, often sold in gasoline for motorcar use, is most effective in this respect and is widely used in aircraft fuels. By adding this compound to aviation fuels which have already been refined to a high octane number, great resistance to detonation may be obtained. Modern aviation fuels used in military and heavy commercial service may have antidetonation characteristics better than the reference fuel iso-octane, *i.e.*, octane numbers greater than 100 (see Refs. F1 and F2).

With a given fuel under a given set of operating conditions, the maximum cylinder pressure has a definite limit, and this limit, in turn, limits the compression ratio in unsupercharged engines, and limits both compression ratio and inlet pressure in supercharged engines. This leads to a method of determining the detonation limit for a particular engine by determining the detonation-limited inlet pressure and/or mean effective pressure.

Effect of Fuel-air Ratio on Detonation. Figure 110 shows how fuel-air ratio affects detonation-limited inlet pressure and mean effective pressure with 100-octane fuel at various compression ratios. In the tests on which these curves were based, at each fuel-air ratio the inlet pressure was increased (by means of the supercharger) until detonation started. This figure also shows, at least in part, why fuel-air ratio must be held within a limited range. Such curves depend to a considerable extent on the engine and operating conditions used, and therefore Fig. 110 must be considered as typical, rather than as giving actual figures for any particular case.

This figure shows how increasing the compression ratio reduces the specific fuel consumption (in this case based on indicated horsepower) as would be expected from Fig. 109. It also shows that the maximum allowable mean effective pressure, and hence the maximum allowable power, increases as the compression ratio decreases. Thus, the compression ratio chosen is a compromise between the desire for high power and the desire for high efficiency (low fuel consumption), at least in the case of supercharged engines. As regards unsupercharged engines, Fig. 110 indicates that the highest compression ratio allowable with this fuel (100-octane army gasoline) and this engine is about 8.5. However, most unsupercharged engines use fuel of about 80 octane number, which limits the compression ratio to about 7.0 in the usual case.

Water-alcohol Injection. A very powerful method of controlling detonation is to inject a mixture of water and alcohol (usually a mixture of 50 per cent of each) into the inlet manifold. When this expedient is used, the fuel-air ratio is held to about 0.08, and the water-alcohol flow rate is usually about half the fuel-flow rate. The liquid-air ratio is thus about 0.12, or about the same as in take-off without water-alcohol injection. The specific liquid consumption under these circumstances is high (in the neighborhood of 1 lb per bhp per hr) so that it is not feasible to use water-alcohol injection except for short periods, such as take-off or active combat. Otherwise, too great a load of the fluid would have to be carried. This device usually allows a temporary increase in power of about 20 per cent over that which is allowable without it.

Given all the above expedients, namely, the use of a high-octane fuel, a high fuel-air ratio, and if necessary, water-alcohol injection, there is still a maximum inlet pressure, and hence a maximum inlet density above which detonation will occur with a given compression ratio. Modern reciprocating aircraft engines all use compression ratios in the

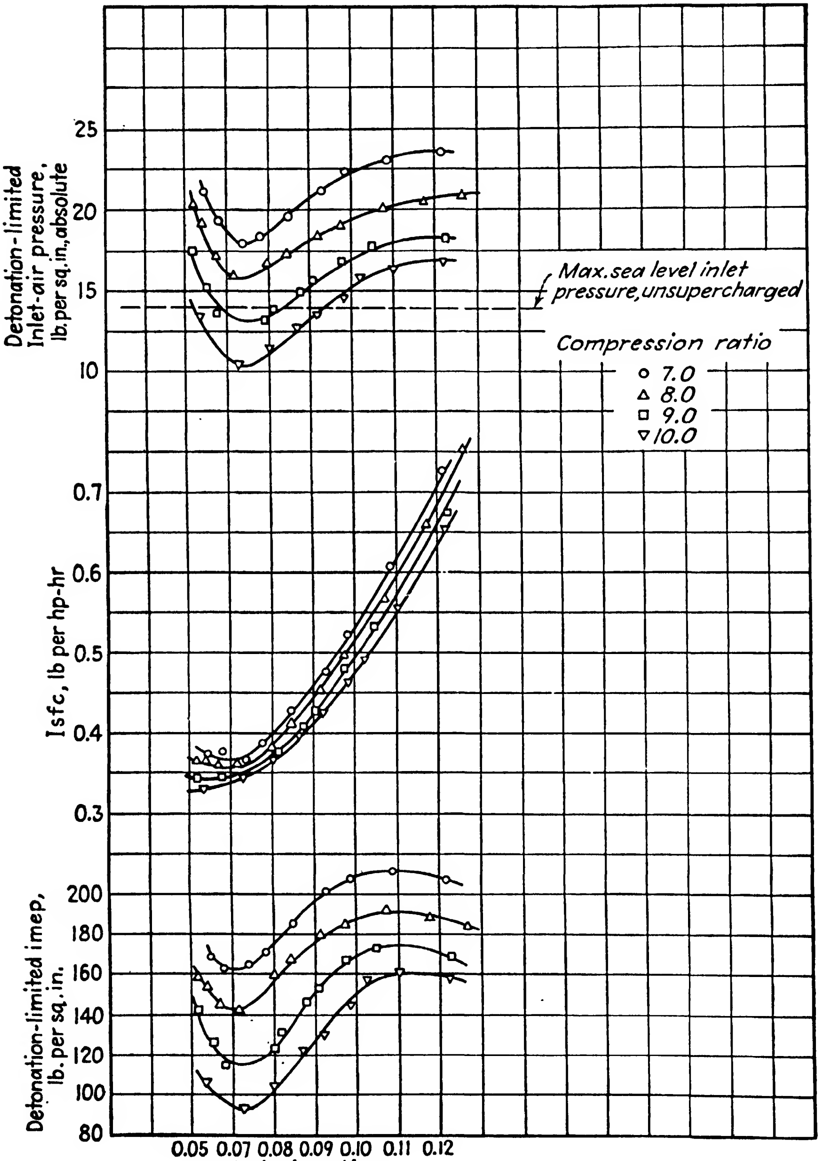


FIG. 110. Detonation limited inlet pressure, indicated mean effective pressure and indicated specific fuel consumption vs. fuel-air ratio and compression ratio. Wright 1820 G200, single-cylinder test engine; oil-out temperature, 170°F; spark advance, 20° B.T.C.; engine speed, 1,600 rpm; inlet-air temperature, 250°F; cooling-air pressure drop, 6.5 in. of water; fuel, Army octane gasoline. (*Courtesy National Advisory Committee for Aeronautics from ARR* 4C31, *March,* 1944.)

neighborhood of 7. Their detonation-limited inlet pressure depends on fuel composition, fuel-air ratio, inlet temperature, and rpm, and on whether or not water-alcohol injection is being used. Table 4 (page 124) gives take-off inlet pressures for a number of current engines using fuels typical of current (1948) practice.

Limitations on Crankshaft Speed. Light aircraft engines usually have their propellers mounted directly on the end of the crankshaft. In such cases the maximum crankshaft rpm is limited by considerations of propeller efficiency (see Chap. X). For engines of this type, the maximum rpm at take-off does not usually exceed 2,500.

Most large engines drive their propellers through gears, as indicated in Fig. 63. In such cases, the maximum crankshaft rpm is limited only by the stresses which high speed imposes on the working parts. In engines of similar design, these stresses are the same when the *average piston speed* is the same. The average piston speed is defined as $2SN$, which is the distance in feet which a piston travels in 1 min (S = stroke in feet, N = rpm). Modern large aircraft engines employ piston speeds of about 3,000 ft per min for take-off and 2,000 ft per min for cruising. Having set the piston speed with a given stroke, N is obviously determined. In most modern airplane engines, except for the light-plane class, the stroke is near 6 in., in which case the take-off rpm is near 3,000 (see Table 4).

Limitations on Fuel-air Ratio. From Eq. (9) it might at first be assumed that power can be increased indefinitely by increasing the fuel-air ratio. This is not the case, however, since increasing fuel-air ratio reduces ideal efficiency (Fig. 109). Actually, if detonation does not interfere, the fuel-air ratio giving maximum power is that at which the product FE_i is a maximum. With gasoline this maximum occurs at $F = 0.075$, which is therefore called the *maximum-power* fuel-air ratio. However, when detonation constitutes the limitation, the fuel-air ratio for maximum power is about 0.10, as shown by Fig. 110.

Maximum efficiency cannot be increased indefinitely by decreasing fuel-air ratio because below about $F = 0.06$ the efficiency ratio E_r in Eq. (9) decreases faster than the efficiency increases. This decrease is due to the fact that combustion becomes very slow below $F = 0.06$. Consequently, best efficiency, *i.e.*, the lowest specific fuel consumption, in actual engines is obtained at about $F = 0.06$ (see Fig. 110).

In actual practice, the fuel-air ratio used varies with per cent of rated power being used, as already indicated by Fig. 70. Figure 111 gives specific-fuel-consumption data corresponding to the fuel-air-ratio data of Fig. 70. The fuel-air-ratio schedule shown in Fig. 70 is dictated by

the considerations which follow. At high power, high fuel-air ratios must be used to prevent detonation, in spite of the fact that a sacrifice in fuel economy is involved. As the load is reduced, a point is reached where detonation is no longer a limitation, and the fuel-air ratio can be reduced to secure low fuel consumption. It cannot be reduced below about 0.06, however, for reasons previously given. Cruising is generally carried out in the range where low fuel-air ratio can be used. For good light-load operation and idling, higher fuel-air ratios are again required, but here specific fuel consumption is always high on account of poor mechanical efficiency. It should be noted, however, that the relatively poor fuel economy associated with heavy and light loads is not a serious drawback, since airplanes operate in either of these regions only a small fraction of their operating time.

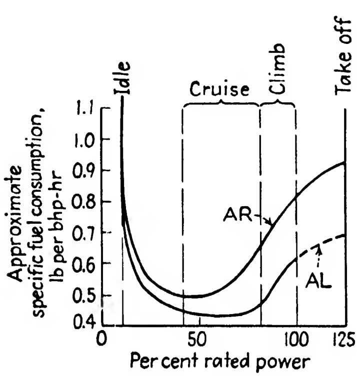


FIG. 111. Specific fuel consumption vs. power for a typical supercharged airplane engine. AR indicates "automatic rich" setting of carburetor control and AL indicates "automatic lean." AR is always used for take-off; AL is generally used for cruising (compare with Fig. 70).

Altitude Performance of Reciprocating Engines. Figure 112 shows the variation of power with altitude for three types of reciprocating engine. These curves are for the "standard" temperatures and pressures shown in Fig. 6, and for a constant crankshaft rpm in each case.

Referring to Eq. (9), changes in altitude affect chiefly inlet density and mechanical efficiency. For the unsupercharged engine, inlet density is nearly proportional to atmospheric density at all altitudes. However, the power required to overcome friction is nearly the same at any altitude as it is at sea level, and as the indicated power decreases, the mechanical efficiency decreases, with the result that the maximum brake power falls off faster than the density, as indicated by curve A. Half normal rated power occurs at about 16,000 ft, and at 30,000 ft the maximum power is reduced to about 22 per cent of the normal sea-level value. Thus, unsupercharged engines are unsuited to high-altitude operation.

As we have already pointed out, the power of supercharged engines at low altitudes is limited by questions of detonation and internal stresses to arbitrary values specified by the manufacturer. Thus, "normal rated power" is usually specified as the maximum power for

continuous reliable operation. Supercharged engines are generally limited to this power except for take-off and in emergencies. Thus the curve of normal power (*B* and *C*, Fig. 112) is independent of altitude up to the altitude at which the throttle is wide open and the normal

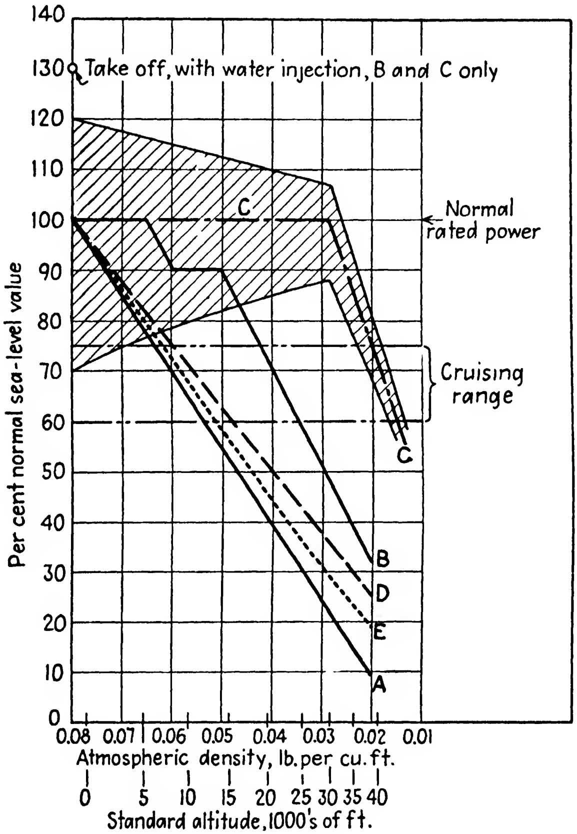


FIG. 112. Shaft power of reciprocating engines vs. altitude. Typical curves for U.S. engines. *A*. Unsupercharged engines, full throttle. *B*. Supercharged engine, two-speed gear-driven supercharger. *C*. Supercharged engine, with exhaust-turbo supercharger and intercooler. *D*. Atmospheric density. *E*. Atmospheric pressure. Shaded area shows range of curve *C* with temperature extremes of Table 7. [All curves for constant rpm (normal rated except at take-off.)]

power can just be maintained. This altitude is called the *critical altitude* of the engine-supercharger combination. By this definition, the critical altitude of an unsupercharged engine is sea level.

Above their critical altitudes, supercharged engines behave in the same way as unsupercharged engines, because they are subject to the

same decrease in inlet density and decrease in mechanical efficiency as altitude increases.

Curve *B* of Fig. 112 is typical for an engine with a two-speed, gear-driven, single-stage supercharger. The critical altitude with supercharger in low gear is usually about 5,000 ft, and in high gear about 15,000 ft. As indicated by Fig. 112, such an engine will give about 90 per cent of normal rated power at 15,000 ft and nearly 50 per cent at 30,000 ft. If normal cruising power is taken as 50 per cent of take-off power (65 per cent of normal rated power), this power is available up to about 23,000 ft. Below the critical altitude, with either gear ratio, the engine must be throttled so as to hold power to the specified limit.

Although it is possible to increase the power at high altitudes over that shown in curve *B* (Fig. 112) by using a two-stage gear-driven supercharger, in American practice it is more usual to employ an auxiliary exhaust-turbine-driven supercharger for this purpose. Such a supercharger is usually used in conjunction with a gear-driven supercharger of low critical altitude, and thus forms the first stage of a two-stage supercharger combination. The exhaust-turbine-driven supercharger can be designed so as to maintain a constant pressure at the gear-driven-supercharger inlet, with an exhaust pressure no greater than standard sea-level pressure. This means that engine inlet pressure and engine exhaust pressure can be held substantially constant up to the critical altitude, and if an effective intercooler is used, engine inlet density can also be held constant. Thus, the engine brake horsepower can be held constant up to the designed critical altitude. Figure 112 shows the performance of such a combination with a critical altitude of 30,000 ft. Cruising power can evidently be maintained to 40,000 ft, or higher than is now considered practicable for continuous operation.

It should not be concluded from Fig. 112 that supercharged engines have no advantage over unsupercharged engines at sea-level and low altitudes. For a given output at take-off and at low altitudes, the supercharged engine can be built for about half the weight of the corresponding unsupercharged engine. The only reason for using an unsupercharged engine is for the sake of mechanical simplicity and low engine cost in small airplanes, where minimum engine weight and good performance at high altitudes are not of critical importance.

Effect of Atmospheric Temperature. The atmospheric temperature at any flying altitude can vary widely with geographic location, season, and weather. For this reason, "altitude" is usually defined on the

basis of the existing atmospheric pressure, according to the standard curve given in Fig. 6. Altitude defined in this way is called *pressure-altitude,* and is the altitude commonly referred to in discussions of airplane and engine performance. For airplanes which are to fly in all climates, it is generally considered that the extremes of temperature shown in Table 7 should be allowed for.

TABLE 7. PROBABLE TEMPERATURE EXTREMES IN WORLD-WIDE FLYING

Pressure-altitude, ft	Air temperature, °F		
	NACA standard	Maximum	Minimum
0	60	130	−65
10,000	24	100	−72
20,000	− 9	65	−80
30,000	−44	27	−90
40,000	−67	−5	−97

With any type of engine, supercharged or unsupercharged, the inlet temperature goes up and down with atmospheric temperature. At a given pressure, airflow and hence indicated power of reciprocating engines vary inversely as the square root of the inlet temperature as long as there is no change in fuel-air ratio, speed, or throttle setting. However, the tendency toward detonation increases rapidly with increasing inlet temperature, so it becomes necessary to *throttle* the engine slightly in order to stay below the detonation limit as atmospheric temperature increases above standard. Conversely, it is possible to open the throttle to a slightly higher inlet pressure as the temperature decreases below normal, provided detonation is the only limiting factor. However, if the manufacturer imposes a limit on maximum power on account of mechanical stresses, it may not be possible to take advantage of reduced temperatures in this way.

Figure 112 shows estimated detonation-limited power variation with temperature with a normal fuel (based on the extreme temperature variations of Table 7) for the turbosupercharged engine. Even at the highest temperatures, it is evident that a cruising power of 65 per cent normal could be maintained, but that the take-off power is very seriously reduced.

Specific Fuel Consumption. As we have seen [Eq. (5)], specific fuel consumption is inversely proportional to the efficiency, *i.e.*, inversely proportional to $E_iE_rE_m$. With a given engine, these efficiencies depend

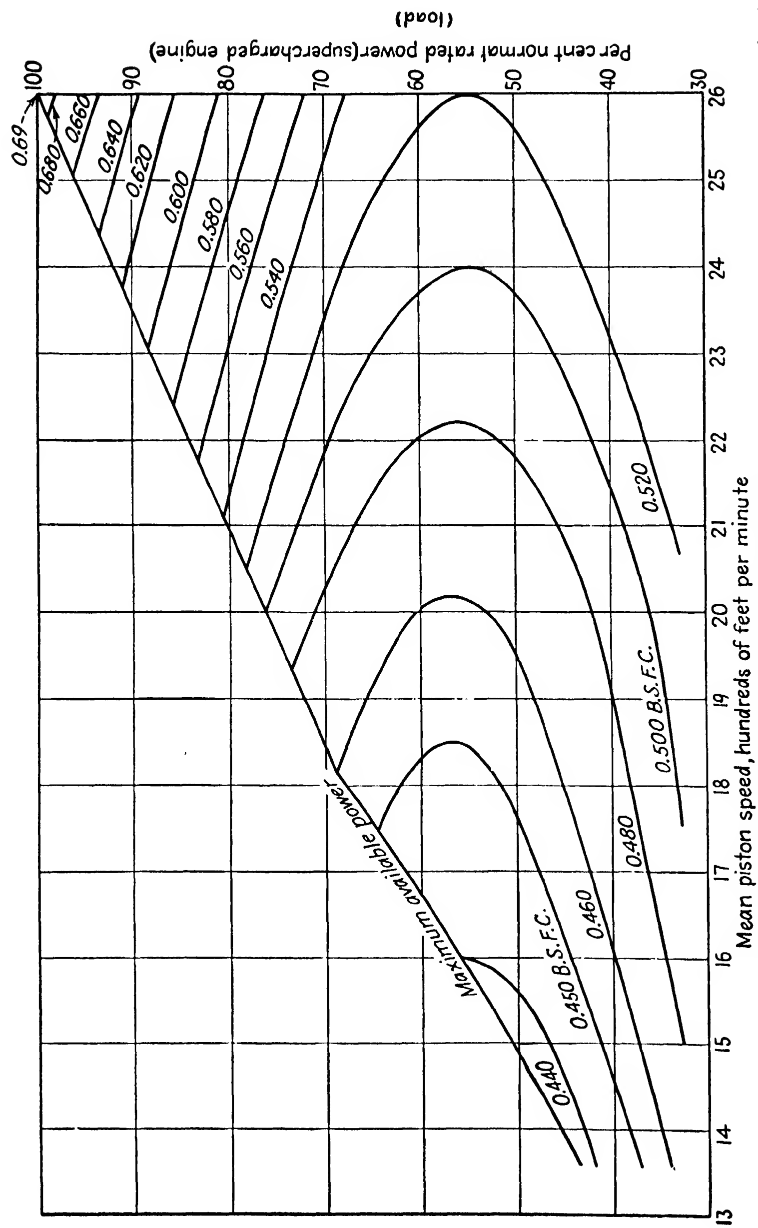


FIG. 113. Brake-specific-fuel-consumption curves for a typical supercharged airplane engine. (Automatic lean carburetor setting.)

chiefly on fuel-air ratio, piston speed, and *load, i.e.*, ratio of power being developed to rated power.

Figure 113 shows that the lowest fuel consumption at a given load is obtained at the lowest piston speed at which the desired power can be produced. The reason is that friction power decreases, and hence mechanical efficiency increases, as the piston speed goes down.

Figure 113 also shows that specific fuel consumption tends to be high at light loads. This is again chiefly a result of reduced mechanical efficiency, because at a given piston speed, friction power tends to remain constant. Thus, as load is reduced, a greater fraction of the work on the piston goes into overcoming friction.

Figure 113 further shows that specific fuel consumption tends to be high at heavy loads, in spite of the fact that mechanical efficiency is high under these conditions. The explanation lies in the use of rich mixtures at heavy loads to protect the engine against detonation and overheating (see Fig. 70). With rich mixtures, ideal efficiencies, and therefore actual efficiencies, are low.

High atmospheric temperatures may tend to cause increases in specific fuel consumption, because with high inlet temperatures, it may be necessary to operate the engine at increased cruising speed in order to obtain the desired cruising power.

Effect of Airplane Speed. The engine air inlet is usually located in such a position that it receives the dynamic pressure q, due to airplane forward speed (see page 17). Where the engine can be operated at wide-open throttle, *i.e.*, above its critical altitude, the maximum available power will be nearly proportional to $p_a + q$, where p_a is the atmospheric pressure. Thus, at high altitudes where p_a is small, high airplane speed will have a very favorable effect on the maximum power available, provided the altitude is above the critical altitude.

Oil Consumption. In the operation of an engine, a certain amount of oil escapes past the piston rings into the cylinders. Much of this oil is blown out the exhaust valves, but some always burns, or partially burns and forms carbon. The engine is said to "consume" all oil which escapes past the piston or leaks out at other places. The oil consumption of aircraft engines must be provided for by a reserve supply of oil, and this may be an important item in the load carried by long-distance airplanes. Oil tankage for reciprocating engines is usually designed to be about one-twentieth of the fuel tankage, and the oil consumption of a reciprocating engine in good condition should not exceed this amount.

PERFORMANCE OF THE TURBOPROP ENGINE

Ideal Efficiency. The efficiency of the *ideal* gas turbine, operating at the very low fuel-air ratios now in use, depends only on the pressure ratio, *i.e.*, on the ratio of absolute compressor-inlet pressure to absolute compressor-outlet pressure. Calling this ratio r, the ideal efficiency E is obtained as follows:

$$E = 1 - \left(\frac{1}{r}\right)^{0.286} \tag{10}$$

As we have seen, the compression and expansion losses in the reciprocating engine are small (compare the actual and ideal diagram of Fig.

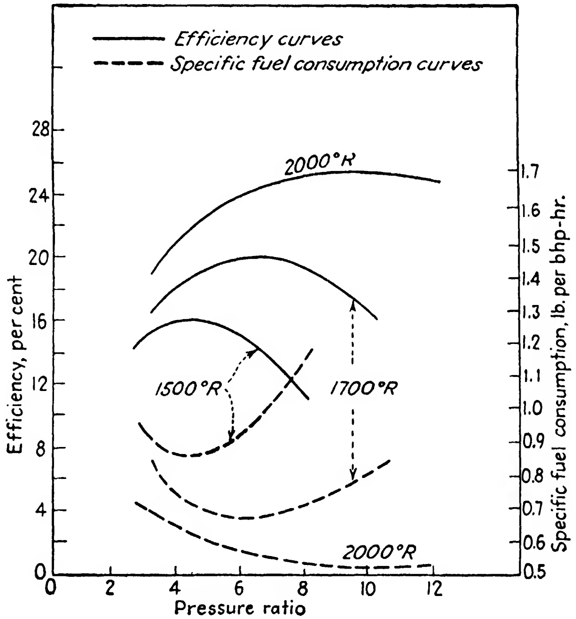


FIG. 114. Thermal efficiency and specific fuel consumption of simple gas turbine at various turbine-entrance temperatures. $E_t = 0.85$, $E_c = 0.84$, $T_1 = 70°F$. No combustion-chamber losses, no heat exchanges. $Q_c = 19{,}000$ Btu per lb. (*Godsey, "Gas Turbines and Aircraft," Jour. SAE, September*, 1946.)

108). On the other hand, the losses in the compressor and turbine of a turboprop engine are considerable and are due chiefly to gas friction and eddy losses in the blading. These losses are similar to those which cause turbulence behind an airfoil, as explained in Chap. II. With good design, turbine and compressor losses can be held to about 15 per cent, based on the ideal process, with the result that the efficiency *ratio*

of a well-designed turboprop engine is about 0.50 at 2000°R turbine inlet temperature. The mechanical efficiency of such engines is about 0.98, since mechanical friction is extremely small. The net result is shown in Fig. 114, which is a plot of efficiency and specific fuel consumption for a well-designed turboprop engine operating at three different turbine entrance temperatures.

It will be noted that efficiency increases as the turbine inlet temperature increases, but that no data are given for temperatures higher than 2000°R. The reason for this omission is that 2000°R is about the highest at which any present gas turbine can be operated without serious damage to the turbine blades, turbine nozzles, or other parts exposed to the hot gases.

Since the blades and nozzles are surrounded at all times by the hot gases, it is difficult to cool them effectively, and they must run at temperatures nearly as high as the gases themselves. The present limit of about 2000°R for the *turbine inlet temperature* is set by the characteristics of the best available blade materials, which are generally metallic alloys containing iron, nickel, chromium, and cobalt in various proportions (see Ref. E19). Ceramic materials are also receiving attention, but are not yet used.

The turbine inlet temperature is controlled by controlling the fuel-air ratio, which cannot exceed about 0.015 for a temperature of 2000°R with pressure ratio of 4. Even this temperature can be used only for short-time operation. The allowable take-off and emergency power can be increased by water injection, which will allow fuel-air ratios as high as about 0.020 without exceeding 2000°R turbine inlet temperature. This expedient, however, can be used for very short periods only, on account of the high rate of water consumption. Continuous operation, such as cruising, must be carried out without water at turbine inlet temperatures not exceeding about 1700°R. This temperature limitation is a great handicap in securing high turbine efficiencies and particularly in securing high output in proportion to the rate of airflow. As means are found to allow higher turbine inlet temperatures, the performance of turboprop and turbojet engines will improve accordingly.

Power Output. From Eq. (6) and Fig. 114, the power output of a gas turbine can be computed if the fuel-air ratio and rate of airflow are known. As an example, let us compute the power output of a turboprop engine which uses 1,000 lb of air per minute, with compression ratio 6 and 2000°F combustion temperature (fuel-air ratio 0.015). Referring to Fig. 114, the estimated efficiency is 0.24. From Eq. (6),

since Q_c is about 19,000 Btu per lb for turbine fuels,

$$\text{hp} = \frac{1{,}000 \times 0.24 \times 19{,}000 \times 0.015}{42.4}$$
$$= 1{,}610, \text{ or } 1.61 \text{ hp per lb air per minute}$$

The specific fuel consumption, from Fig. 114, will be about 0.58. However, for continuous operation the combustion temperature would have to be reduced to about 1700°R, at which point the efficiency would be 0.20 and the specific fuel consumption 0.67. The fuel-air ratio would be reduced about as the ratio of the temperatures, or to

$$\frac{0.015 \times 1{,}700}{2{,}000} = 0.0127,$$

and maximum cruising power would be

$$\frac{1{,}000 \times 0.20 \times 19{,}000 \times 0.0127}{42.4} = 1{,}140 \text{ hp}$$

Heat Exchangers. The efficiency of a turboprop engine could be increased considerably by introducing a *heat exchanger* in such a way that the air between the compressor outlet and the combustion chambers is heated by the exhaust gas from the turbine. It is evident that with such heating, less fuel will have to be burned to bring the turbine entrance temperature up to a specified limit. The increase in efficiency depends on the size and design of the exchanger, and may be as much as 20 per cent (*e.g.*, from a cruising efficiency of 0.20 to an efficiency of $0.20 \times 1.2 = 0.24$). However, to effect this much gain, the exchanger must be large and heavy, and it would seriously interfere with jet thrust. For aeronautical purposes there is still some doubt as to whether one should be used. (It should be noted that the power output is not increased by the use of a heat exchanger as long as the combustion temperature is held constant.)

As previously mentioned, most turboprop engines are designed to exhaust at a considerable gas velocity, which gives them a certain amount of *jet thrust.* The ratio of pounds jet thrust to shaft horsepower is usually between 0.20 and 0.30 at maximum take-off power.

Altitude Performance. Figure 115 shows performance curves for a typical turboprop engine of the present time. Each curve corresponds to a specified turbine inlet temperature. Power does not decrease as fast as air density for two main reasons, namely:

1. At constant turbine inlet temperature, airflow (by weight) is proportional to the pressure furnished by the compressor. The pressure

ratio of the compressor increases with decreasing inlet temperature, and therefore the compressor outlet pressure and rate of airflow fall off less rapidly than the atmospheric pressure.

2. For constant turbine inlet temperature, the fuel-air ratio is increased as the compressor outlet temperature falls. This is, perhaps,

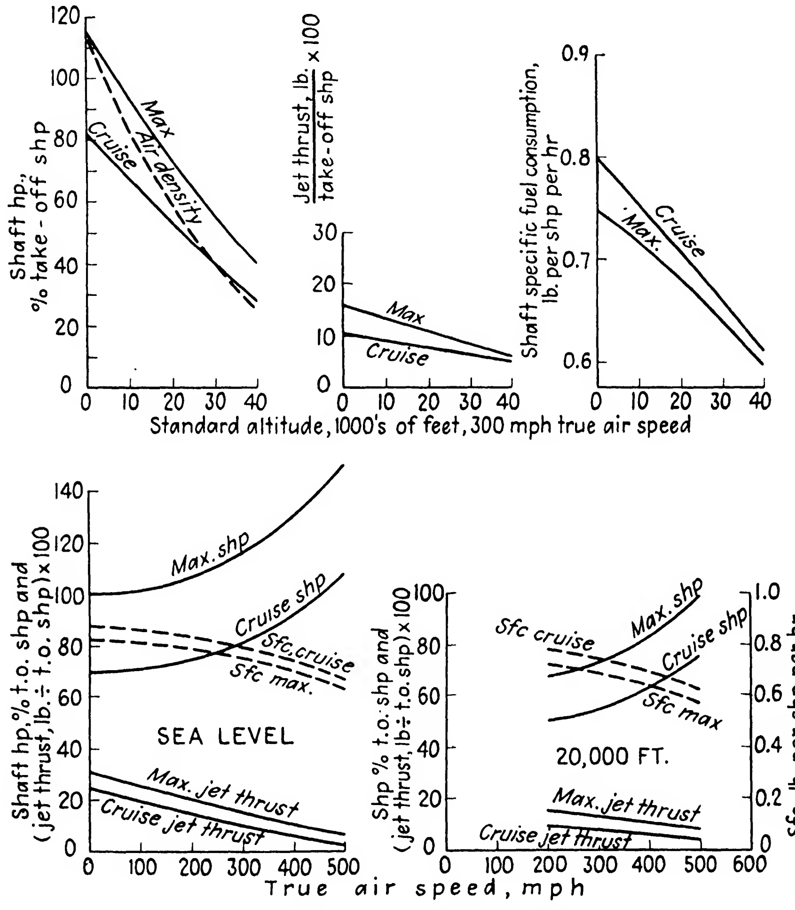


FIG. 115. Power and specific fuel consumption vs. altitude, turbo-propeller engine.

the most important explanation of the fact that power output falls less rapidly than atmospheric density.

Figure 115 shows that while specific fuel consumptions are high at low altitudes, they improve rapidly as altitude increases. This trend is explained by the fact that both pressure ratio and fuel-air ratio

increase with increasing altitude. Figure 114 indicates the favorable effects of increasing pressure ratio in the range 4 to 6. Decreasing inlet temperature with constant turbine entrance temperature is equivalent to increasing turbine entrance temperature at constant inlet temperature. Improvement in specific fuel consumption due to the latter process is shown in Fig. 114.

Effect of Air Temperature. One of the weaknesses of gas turbines is their great sensitivity to increasing atmospheric temperature. As this temperature increases, inlet density decreases, compressor pressure ratio decreases, and fuel-air ratio must be decreased so as not to exceed the allowable turbine inlet temperature. On the other hand, decreasing temperature has the opposite effect, and for a given turbine inlet temperature, power can be relatively high at low air temperatures.

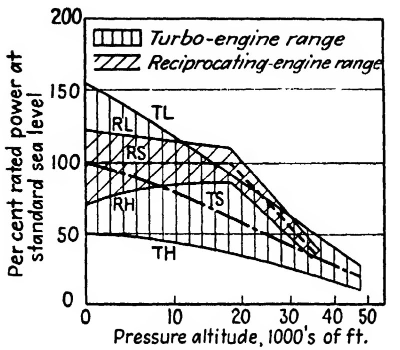


FIG. 116. Estimated variation of maximum power with pressure altitude. TL—turboengines, extreme low temperatures. TS—turboengines, standard temperatures. TH—turboengines, extreme high temperatures. RL—reciprocating engines, extreme low temperatures. RS—reciprocating engines, standard temperatures. RH—reciprocating engines, extreme high temperatures.

Figure 116 shows estimated range of turbo-engine power (or jet thrust) at the extremes of temperature indicated in Table 7. The turbo-type engines are able to maintain only about 50 per cent of their maximum rating at the highest atmospheric temperature, even with their maximum allowable turbine inlet temperatures. For estimating purposes it may be assumed that the maximum power of turboprops or turbojet engines varies inversely as the inlet temperature raised to the 2.5 power.

PERFORMANCE OF TURBOJET ENGINES

In order to discuss this subject, it is necessary to define *kinetic energy*. This term may be defined as the work required to slow down a given mass of material to zero velocity, or the work required to bring the material up to a specified velocity from rest. This work is found to be $Mv^2/2g$, where M is the weight of material, v is the velocity in question, and g is the acceleration of gravity, which is 32.2 ft per sec per sec. The unit of kinetic energy is, of course, the same as the unit of work: in this case, the foot-pound.

In the case of the jet engine, the power produced is in the form of kinetic energy of the exhaust gases. The kinetic energy of a pound of fluid moving at a velocity of v ft per sec is $v^2/64.4$ ft-lb. Viewed from the airplane, for each pound of air it receives at airplane speed v_a, the jet engine discharges $(1 + F)$ pounds of gas at jet speed v_j. Thus the work w done per pound of air which passes through the jet is the increase in kinetic energy, or

$$w = \frac{1}{64.4}[(1 + F)v_j^2 - v_a^2] \qquad \text{ft-lb} \tag{11}$$

where the velocities are both expressed in feet per second. As already stated, the efficiency of an engine is the work done divided by J times the heat absorbed. The heat absorbed by 1 lb of air in the jet engine is FQ_c Btu, or $778FQ_c$ foot-pounds, where F is the fuel-air ratio and Q_c the heat of combustion of the fuel. Therefore the efficiency of a jet engine is

$$E = \frac{(1 + F)v_j^2 - v_a^2}{64.4 \times 778 \times FQ_c} \tag{12}$$

Since fuel-air ratios are very small (usually not over 0.015), the factor $(1 + F)$ is usually omitted. With this omission, (12) can be rearranged as follows:

$$v_j = \sqrt{50{,}000EFQ_c + v_a{}^2} \tag{13}$$

Thrust. The *thrust* obtained from a jet engine is the reaction force created by accelerating the air from airplane speed to jet speed. This force is calculated as follows:

$$T = \frac{M_a}{32.2 \times 60}(v_j - v_a) \tag{14}$$

where T = thrust, lb

M_a = air flowing through the engine, lb per min

Thrust specific fuel consumption is taken as the pounds of fuel consumed per hour per pound thrust. From (14) this is evidently

$$\text{tsfc} = \frac{60FM_a}{T} = \frac{116{,}000F}{v_j - v_a} \tag{15}$$

Static Thrust. The *static* thrust is the thrust at zero airplane speed. Since this thrust is easy to measure on the ground, and is the thrust at the start of take-off, the *sea-level static* thrust is an important characteristic of any jet engine.

As an example of the use of the equations, let us estimate *static* jet

velocity, static thrust, and static specific fuel consumption for a turbojet engine of pressure ratio 4, using 1,000 lb of air per minute, maximum combustion temperature 2000°R, heat of combustion of fuel 19,000 Btu per lb.

The efficiency will be about the same as indicated in Fig. 114, or 0.20. The fuel-air ratio for 2000°R is about 0.015. Using Eq. (13),

$$v_j = \sqrt{50{,}000 \times 0.20 \times 0.015 \times 19{,}000} = 1{,}690 \text{ ft per sec}$$

Using Eq. (14),

$$T = \frac{1{,}000}{32.2 \times 60} \times 1{,}690 = 873 \text{ lb}$$

or 0.873 lb per lb of air per minute.

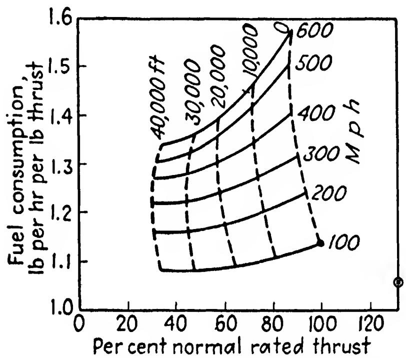


FIG. 117. Flight performance of a typical turbojet engine at maximum cruising output, standard atmospheric conditions. ⊙ represents the rated take-off. (*Computed from P. B. Taylor and S. T. Robinson, "Possibilities of the Turbojet Power Plant," paper read before SAE, June 2–7, 1946.*)

Thrust specific fuel consumption is found from Eq. (15).

$$\text{tsfc} = \frac{0.015 \times 116{,}000}{1{,}690}$$
$$= 1.03 \text{ lb per hr per lb thrust}$$

Thrust Horsepower. Since power is force times distance per unit time, or force times velocity, the *useful* power due to thrust is the product of thrust multiplied by airplane speed. Thus

$$\text{thp} = \frac{60 T v_a}{33{,}000} = \frac{TV}{375} \qquad (16)$$

where v_a is the airplane speed in feet per second and V the same speed in miles per hour. Turbojet engines have the characteristic of giving nearly the same thrust over a wide speed range, at a given altitude. Letting T_s be the static thrust, the thrust power is then approximately $T_sV/375$. Thus, at 375 mph airplane speed the thrust horsepower of a jet engine is approximately equal to its static thrust in pounds.

Since the useful power of a jet engine is directly proportional to airplane speed, it is easy to see why this type of engine is best adapted to very high speed airplanes.

Turbojet Performance. Figure 117 shows performance curves of a typical turbojet engine. The lowest fuel consumption per pound thrust comes at lowest flight speeds, but, of course, this is not the most

economical regime for fuel consumption in terms of *thrust horsepower*. The thrust decreases with altitude, as would be expected. The rated take-off thrust requires a turbine inlet temperature of about 2000°R and cannot be used except for short periods.

The effect of altitude and air temperature on turbojet-engine thrust is about the same as for turboprop engines, and is indicated in Fig. 116.

ROCKET PERFORMANCE

Like the jet engine, the rocket produces thrust by driving hot gases backward from the airplane. Unlike the jet engine, however, the

TABLE 8. ROCKET FUELS

Fuel	Theoretical maximum jet velocity, ft/sec	50% theoretical jet velocity		
		Jet velocity, ft/sec	Pounds thrust per lb/sec fuel supply	Specific fuel cons., lb/hr, per lb thrust
Hydrogen + oxygen	17,100	8,600	267	13.5
Gasoline + oxygen	14,600	7,300	227	15.8
Ethyl alcohol + oxygen	13,700	6,850 7,100*	212 220*	17.0 16.3*
Nitroglycerin (smokeless powder)	12,700	6,350	197	18.3
Hydrogen peroxide + fuel oil	12,000	6,000 5,970†	186 185†	19.3 19.5†
Black gunpowder	8,350	4,175	130	27.7

* Attained in V-2 rocket.
† Attained in Messerschmitt Me-163 fighter.

rocket does not take in air from the atmosphere. Therefore its thrust is obtained by omitting the term v_a from Eq. (14) or

$$T = \frac{M_p v_j}{32.2 \times 60} \tag{17}$$

where M_p is the pounds of propellant burned per minute. The specific propellant consumption in pounds per hour per pound thrust is, from Eq. (5),

$$\text{spc} = \frac{60M_p}{T} = \frac{32.2 \times 60 \times 60}{v_j} = \frac{116,000}{v_j} \tag{18}$$

Propellants. The maximum theoretical jet velocity of a rocket depends only on the proportions and the chemical composition of its propellants. The most important rocket propellants, together with their heats of combustion per pound, their maximum jet velocities, and their minimum specific consumptions are given in Table 8. Well-designed rockets can develop from 0.4 to 0.6 of the theoretical jet velocities given in the table.

Altitude Performance. The effect of atmospheric conditions on rocket thrust is small, since the rocket does not depend on atmospheric air for combustion. What effect there is on rocket-jet thrust is due to atmospheric pressure at the nozzle outlet. This acts as a "back pressure" tending to retard the flow, so that jet thrust increases slightly with increasing altitude.

COMPARISON OF AIRCRAFT POWER PLANTS

The ramjet is not under serious consideration for airplane propulsion at the present time, except in so far as flying bombs and guided missiles may be classed as airplanes. One possible field of usefulness of this type, which should be mentioned, is for helicopters. Ramjets located at the rotor tips of a helicopter could operate at very high air speeds in normal flight and, therefore, might function with reasonable efficiency. Experimental work on this application is already in progress.

Rockets are now accepted as useful devices for assisting take-off of heavily loaded military airplanes. They are not yet used in passenger service, both because of the noise problem and because passenger airplanes, in general, must be flown with loads light enough to allow for continuation of the take-off with one engine out of operation, in which case rocket assistance is not ordinarily required. The use of jet engines for large airplanes with heavy wing loading would appear to require assistance on the take-off, possibly by rockets.

As we have seen, a rocket engine has already been used for one high-speed interceptor fighter, and developments along this line may be expected to continue.

For most airplane purposes, at least for a long time to come, the choice of power plant will lie between the reciprocating engine, the turboprop engine and the turbojet engine. It is therefore worth while to compare these types with each other in some detail.

Comparison of Turbojet, Turboprop, and Reciprocating Engines

While turbojet and turboprop engines have not yet reached the stage of reliability and durability attained by reciprocating aircraft engines,

there is every reason to believe that they can be developed to this point in the reasonably near future. On this account, the following discussion will be based only on their relative *performance characteristics* in terms of power, fuel consumption, weight, noise, and vibration.

Basis of Comparison. In comparing relative power of aircraft engines, *thrust* power is, of course, what counts. Since, at a given air speed, thrust power is proportional to thrust, relative thrust at a given air speed seems the appropriate basis of comparison. However, the useful or *net* thrust is not the propeller thrust but the propeller thrust minus the parasite drag added to the airplane by the engine, owing to its nacelle, cooling system, and auxiliaries. The drag due to transporting the power plant should also be subtracted for a complete comparison. However, this item is rather small in comparison with the others and is difficult to estimate in a general manner. It is, therefore, omitted in the estimates which follow.

A difficulty in making significant comparisons is the fact that a given propeller will give best efficiency only over a restricted range of air speed and altitude (see Chap. X). To overcome this difficulty in comparing power plants, it is assumed in each case that the best propeller is used at each altitude and flight speed. Thus, *optimum* performance, rather than the performance of any one combination of engine and propeller, is assumed in the comparisons which follow.

Net Thrust versus Altitude and Air Temperature. In order to consider these effects, it is necessary to assume the same air speed for all power plants, and to select the size of each plant so as to give the same net thrust at this speed, at standard sea-level conditions.

Since, at constant air speed, thrust and thrust power are proportional to each other, Fig. 116 represents relative net thrust under the conditions specified in the previous paragraph. This figure indicates that turbosupercharged reciprocating engine has the best high-altitude performance when temperatures are normal or above normal. At very low temperatures, however, the turbine-type power plants have the advantage, except near the critical altitude of the reciprocating engine.

The reasons for the relative behavior illustrated in Fig. 116 have already been discussed. It is well to recall at this point, however, that below its critical altitude, reciprocating-engine output is limited by throttling in order to limit internal stresses and to avoid detonation. The maximum output of the turbo engines, on the other hand, is limited by atmospheric conditions and by controlling the fuel-air ratio to give a specified maximum turbine inlet temperature.

Net Thrust versus Flight Speed. Figure 118 shows estimated relative net thrust vs. flight speed of the three types of engines when they

are selected so as to have the same net thrust at 375 mph at sea level. The value of such curves depends on the validity of the assumptions used in computing them. The assumptions used for Fig. 118 are given in Table 9 and are believed to be reasonably representative of current best practice.

The low thrust of the jet engine at take-off is one of its outstanding disadvantages. For this reason, jet-powered airplanes must have

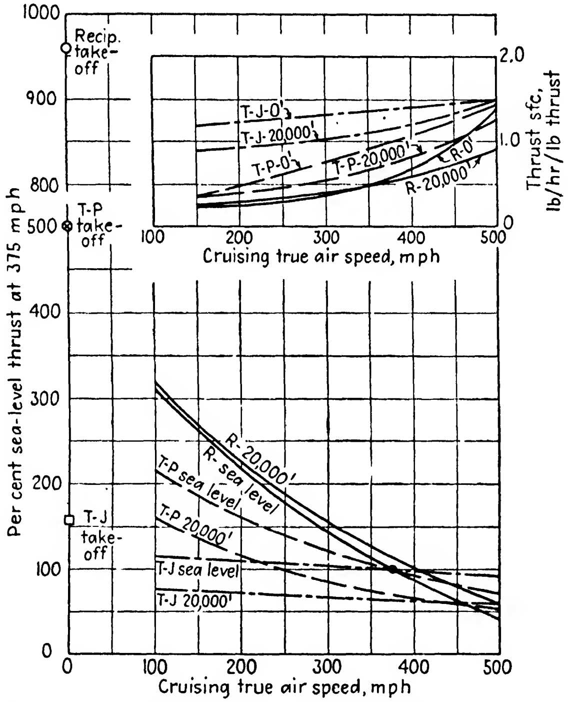


FIG. 118. Relative cruising performance of reciprocating (turbosupercharged) engine, turboprop engine, and turbojet engine, all having same net cruising thrust at 375 mph sea level. (For assumptions see Table 9.)

extremely low power loadings (based on propulsive power at 375 mph), or else they will require take-off assistance. Low power loadings are, of course, characteristic of airplanes having very high maximum speeds, and this is a usual characteristic of jet-powered airplanes.

Comparative Specific Fuel Consumption. Figure 118 also shows estimated specific fuel consumption based on net thrust for the three types of power plant, when they have equal cruising thrust at 375 mph at sea level. The great advantage of the reciprocating engine as well as the serious deficiency of the jet engine at low flight speeds is evident.

At sea level, the thrust specific fuel consumption of all three types seems to approach the same value at about 600 mph. At 20,000 ft, however, the reciprocating engine maintains its advantage up to high flight speeds, owing to the reduced part which nacelle drag plays at this altitude.

TABLE 9. ASSUMPTIONS FOR FIGURES 118, 119, AND 120

Item	Reciprocating engine	Turboprop engine	Turbojet engine
Net thrust at 375 mhp, lb	1,000	1,000	1,000
Altitude performance	Fig. 112	Fig. 115	Fig. 117
Ratio cruise horsepower and jet thrust to take-off shaft horsepower and jet thrust	0.50	Fig. 115	Fig. 117
Nacelle max. cross section, sq ft, per take-off shaft horsepower (or take-off thrust for jet engines)	0.005	0.0033	0.002
Nacelle drag coefficient:			
100–375 mph	0.0556	0.0556	0.0556
500 mph	0.060	0.060	0.060
Propeller efficiency:			
100 mph	0.85	0.85	
375 mph	0.85	0.85	
500 mph	0.80	0.80	
Specific fuel and oil consumption based on shaft horsepower	0.43	Fig. 115	
Specific fuel consumption based on thrust	....	....	Fig. 117
Take-off shaft horsepower	2,670	1,300	
Take-off propeller thrust, lb/shp	3.5	3.5	
Take-off exhaust thrust, lb/shp	0.10	Fig. 115	Fig. 117

Comparative Weights. Figure 119 shows comparative weights of the three types of power plants vs. designed flight speed, all installations having the same net thrust at each flight speed. Weights are based on the assumptions of Table 9 and the weights given in Table 10.

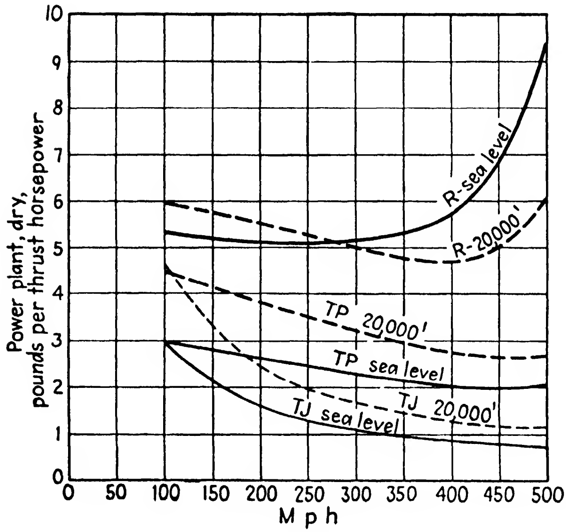


FIG. 119. Power-plant weight vs. cruising flight speed, based on cruising horsepower. Fuel, oil, and tanks not included. Power plants have same thrust horsepower at each flight speed. Best propeller used at each flight speed. R—reciprocating engine, TP—turbopropeller engine, TJ—turbojet engine. (For assumptions see Tables 9 and 10.)

TABLE 10. WEIGHT ASSUMPTIONS FOR FIGURES 119 AND 120

Item	Reciprocating	Turboprop	Turbojet
Bare engine weight:			
Pounds per take-off shaft horsepower......	1.0	0.6	
Pounds per pound take-off thrust.........	....	....	0.4
Installation weight, including engine but without propeller:			
Pounds per take-off shaft horsepower......	1.8	1.2	
Pounds per pound take-off thrust.........	....	....	0.6
Propeller weight, lb/shp at cruise:			
At sea level:			
100 mph............	1.10	1.10	
200 mph............	0.82	0.82	
375 mph............	0.50	0.50	
500 mph............	0.30	0.30	
At 20,000 ft:			
100 mph............	1.6	1.6	
200 mph............	1.2	1.2	
375 mph............	0.72	0.72	
500 mph............	0.44	0.44	
Fuel tank weight, % fuel weight............	10	10	10

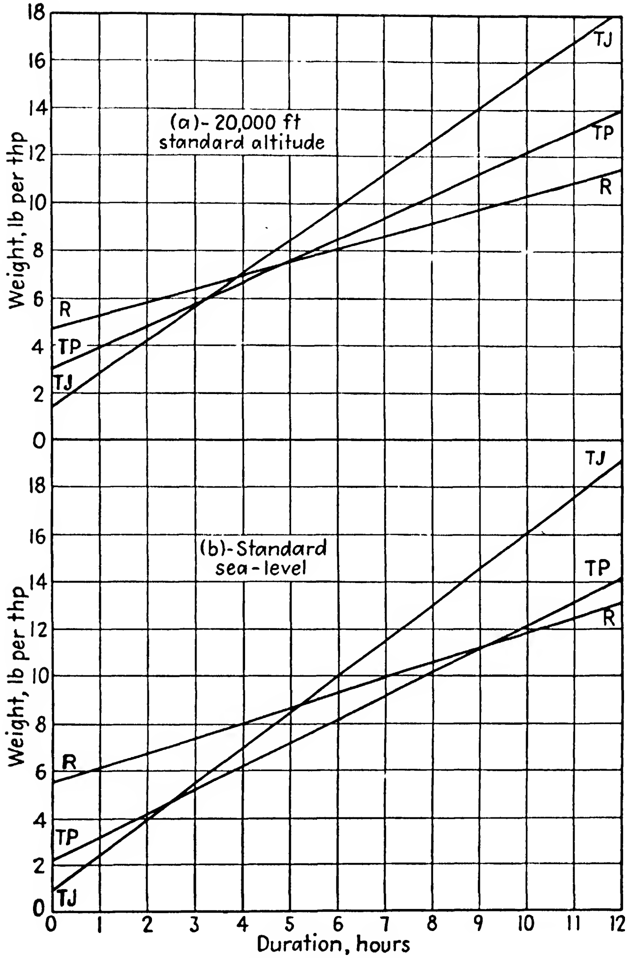


FIG. 120. Estimated take-off weights of power plant, fuel, oil, and tanks vs. flight duration at 375 mph cruise, based on cruising net thrust. TJ—turbojet engine, TP—turboprop engine. R—reciprocating engine. (For assumptions see Tables 9 and 10.)

While the weight comparison given by Fig. 119 is of interest, in order to judge the question of weight in its true perspective, the weight of fuel, oil, and tanks must be taken into consideration.

Figure 120 shows estimated take-off weights of complete power plants including fuel, oil, and tankage vs. hours duration for the three types, assuming 375 mph cruising speed. Other assumptions are covered by Tables 9 and 10. For this flight speed it is evident that

1. *At 20,000 ft standard altitude:*
   The turbojet weight is least up to 3¼ hr duration.
   The reciprocating-engine weight is least beyond 5 hr duration.
   The turboprop weight is least in the range of 3¼ to 5 hr.
2. *At standard sea-level conditions:*
   The turbojet weight is least up to 2½ hr duration.
   The reciprocating-engine weight is least beyond 9 hr duration.
   The turboprop weight is least in the range 2½ to 9 hr.

A lowered cruising flight speed would, of course, be more favorable to the reciprocating engine, and increasing the cruising flight speed would improve the relative position of the jet engine on these plots.

Reciprocating-engine–turbine Combinations. A fourth type of power plant which has received much theoretical attention is the combination of a supercharged reciprocating engine with an exhaust turbine large enough not only to drive the supercharger but to deliver power to the propeller shaft through gearing (see Ref. E22). It is generally admitted that such a power plant would have a cruising specific fuel consumption even lower than that of the conventional reciprocating power plant, and might be slightly lighter for the same cruising power. Its high-altitude characteristics would be particularly attractive. Whether or not the improved fuel economy would justify the added complication and development expense has not yet been established.

Vibration. One of the serious faults of the reciprocating engine is vibration due to the moving parts. In spite of important improvements in isolating engine vibration from the airplane structure, airplane vibration excited by the engine still remains a serious problem. The turbo engines have a great advantage in this respect. Propellers are also a source of considerable vibration, and here the turbojet engine has a distinct advantage.

Noise. Engine noise comes chiefly from two sources: the exhaust and the propeller. Although at the present time the propeller is usually the chief offender, it has been found possible to reduce propeller noise greatly by lowering tip speeds and reducing blade loading (see Chap. X). Thus, propeller noise can be reduced to inoffensive proportions as soon as required, by public demand or otherwise.

Exhaust noise can be reduced to an acceptable level in reciprocating engines by means of suitable mufflers. The exhaust of turbo engines, on the other hand, cannot be "muffled" without seriously interfering with thrust. Thus, the reciprocating engine possesses an important potential advantage in this respect, while the turbojet engine is at a great disadvantage on account of its very high exhaust velocity.

On the whole, it appears that reciprocating-engine noise is subject to control and could be greatly reduced if required. To a lesser extent, this is true for turboprop engines, but the turbojet engine must remain a powerful noisemaker.

Summary of Type Comparisons

The comparative data given in Figs. 118, 119, and 120 do not indicate that any one of the three types of power plants is best for all purposes. The following general conclusions, however, seem justified, at least for the near future.

1. The reciprocating engine is best for flights of very long duration, on account of its low specific fuel consumption. It is also best for light and medium-sized airplanes because of its low cost per rated horsepower when unsupercharged, and because it is difficult to build efficient turboengines in very small sizes.

2. The turbojet engine is unquestionably best for very high speed operation, not only because of its extreme light weight and small size in proportion to thrust developed at high speeds, but also because above about 500 mph its specific fuel consumption is nearly as good as that of either of its competitors. For very high speed airplanes, the fact that take-off thrust does not greatly exceed high-speed thrust is not a serious disadvantage, since the thrust required to attain very high speeds is usually adequate for take-off, unless wing loading is very high. In the latter case, take-off assistance may be required, as previously mentioned.

3. The turboprop engine with a considerable percentage of jet thrust will probably find a useful field of application between the very long distance and very high speed applications, as soon as such engines have been developed to a degree satisfactory for service use.

4. The combination of reciprocating engine and exhaust turbine is an interesting possibility, chiefly on account of its low specific fuel consumption.

5. From the point of view of vibration, the advantage lies with the turbojet engine, while, potentially at least, the reciprocating engine can probably be made to have the lowest noise level.

CHAPTER X

PROPULSION AND THE PROPELLER

Each of the types of power plants that are fitted in airplanes makes the thrust needed to fly the airplane by forcing backward a jet of air or gas. A propeller moves a column of air. The jet of gases discharged by a turbojet engine is made from air with roughly 2 per cent by weight of fuel added; hence the weight of the gases is only 2 per cent greater than the weight of air taken in by the compresser. On the contrary, the rocket engine takes in no air, and the jet discharged results from burning chemicals within the rocket.

For the propeller and the turbojet, losses suffered in making the jet may be studied by applying simple principles of physics to the flow of air. For the rocket such a study is complicated by the rapid loss of weight of the rocket as the chemicals burn.

To produce the thrust needed by the plane, the propeller or turbojet gives to a quantity of originally still air a backward velocity. The kinetic energy of this air is a loss. The thrust varies as the quantity of air times the velocity given it, while the kinetic energy lost varies as the quantity times the square of the velocity. Hence the energy loss for a given ph. is least for the device which handles the largest quantity of air. This conclusion is similar to that reached for reduction in induced drag (*i.e.*, increase air mass flow) and results from the same fundamental reasons. A propeller moves a large quantity of air slowly; a turbojet moves a much smaller quantity rapidly. For the propeller or turbojet, the quantity is increased when the plane speed, air or jet density, or diameter is larger. An ideal propeller would have no loss except that of the kinetic energy in the *slipstream*, but the actual propeller has several others. A turbojet has no other propulsive losses.

The ideal efficiency of a propeller or jet may be defined as the output divided by the output plus the unavoidable loss in the slipstream. Let T be the thrust, M the mass flow of air in pounds per minute, v_s the velocity of the slipstream or jet relative to the airplane, and v the velocity of the airplane, both velocities being in feet per second.

$$T = \frac{M(v_s - v)}{60 \times 32.2} \qquad \text{thrust} \tag{1}$$

$$\text{Output} = Tv = \frac{M(v_s - v)v}{60 \times 32.2} \quad \text{thrust power} \tag{2}$$

$$\text{Loss} = \frac{M(v_s - v)^2}{2 \times 60 \times 32.2} \tag{3}$$

$$\text{Efficiency } E_{\text{ideal}} = \frac{\text{output}}{\text{output} + \text{loss}} = \frac{(v_s - v)v}{(v_s - v)v + \frac{1}{2}(v_s - v)^2}$$

$$= \frac{2v}{v + v_s} = \frac{1}{1 + [(v_s - v)/2v]} \tag{4}$$

The ratio $(v_s - v)/v$ for a propeller varies in flight from about 0.03 to 0.25; the corresponding ratio for a turbojet is about 2 to 8. This large difference results from the extremely small diameter of the turbojet and also is large because of the high jet temperature of the turbojet. Hence the ideal efficiency is greater for the propeller than for the turbojet. Even when all other losses of the propeller are included, its efficiency at speeds up to nearly 600 mph is larger than the propulsive efficiency of the turbojet, but the latter provides, for speeds about 550 mph or more, a power package light and small enough to make such planes practicable. Hence turbojets are used in fighters and high-speed bombers.

Since the turbojet engine has already been considered, the remainder of this chapter will discuss the propeller.

The output of the propeller is the thrust power or *thrust horsepower*, if horsepower is used as the unit of power measurement (remember a horsepower means doing work at the rate of 550 ft-lb per sec). The power input to the propeller must be the thrust horsepower plus all the lost or wasted power and must be the same as the *brake horsepower* delivered along the propeller shaft by either a reciprocating or turboprop engine. The efficiency of the propeller is the ratio of the thrust horsepower to the brake horsepower. It varies from about 50 per cent at take-off to as high as 85 or occasionally 90 per cent in normal flight. The wasted power is lost in the rotation of the slipstream, in making eddies, and by the profile drag of the blade sections, as well as in making the slipstream.

The propeller has two or more twisted blades or airfoil cross sections (Fig. 121). These fit into a *hub* or are joined rigidly in a *boss* which fits a hub. The hub is turned by the propeller shaft of the engine through *splines* or *keys*. In small reciprocating engines, the propeller shaft is part of the engine *crankshaft*, but in larger reciprocating engines or turbines, the propeller is driven by the engine shaft through *reduction gears*. This geared drive is needed to reduce the speed of the propeller tips without restricting the rpm of the engine. Usually the propeller

shaft is short, so that shaft and propeller are supported by the engine crankcase. Infrequently, the propeller is remote from the engine, supported by extra structure and bearings, driven by *extension* shafts

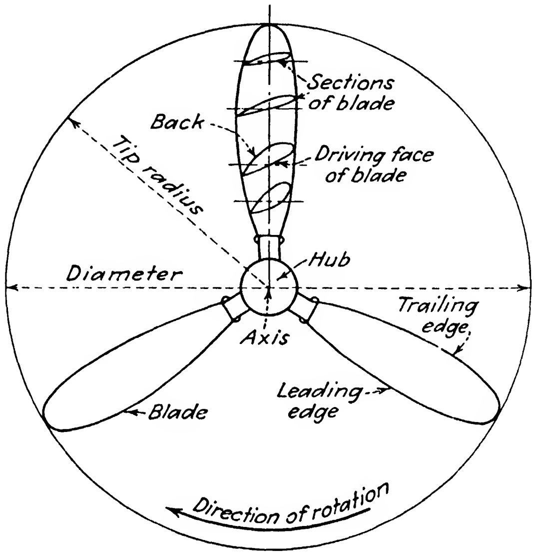


FIG. 121. Propeller parts.

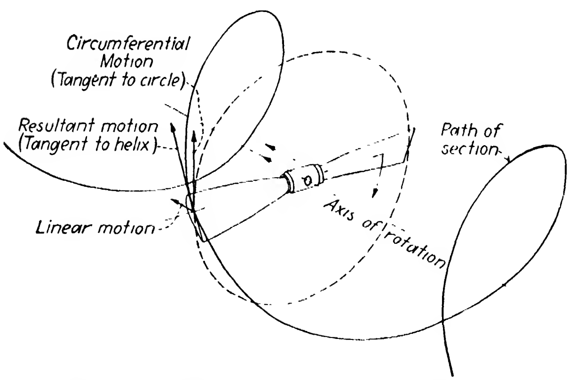


FIG. 122. Motion of one propeller-blade section.

through gears or possibly belts. The axis of the propeller shaft is called the *thrust line.*

Owing to the rotation about the axis, any section of a blade moves on the circumference of a circle; simultaneously, the propeller has a forward velocity V, so the section is also moving forward. The resultant motion is, therefore, along a spiral or *helical* path, as sketched on Fig.

122. The path of one section is shown, and the outer portion of the blades is removed for clarity. Figure 123 gives a close-up of the velocities of a propeller section. The forward velocity (the same at all sections) combines with the circumferential velocity ($2\pi rn$, different at each radius) to determine the *path angle.* The *blade angle*, the angle between the chord of the airfoil section and the propeller disc, minus the path angle, gives the angle of attack. Like any airfoil, this section will give a lift depending on the width of chord, the lift coefficient as determined by the angle of attack, and the dynamic pressure. The dynamic pressure must be calculated from the resultant velocity along the helical path. Any lifting airfoil gives to the air it affects a downward velocity, perpendicular to the resultant velocity. In the case of the propeller section, this downward velocity may be divided into two components: the axial one is the rearward velocity given to the air, originally still, that produces the thrust; the other gives the twist to the slipstream. Thus the rotating propeller produces the slipstream.

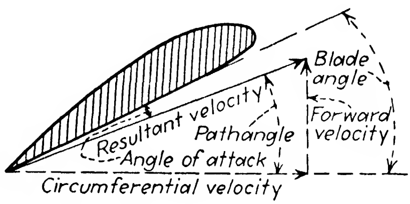


FIG. 123. Propeller section as an airfoil.

The thrust of the whole propeller may be found by adding together the axial components of the forces on each section. The torque required to turn the propeller may be found by adding the circumferential components of the forces on the sections, each multiplied by its proper radius (see Fig. 124). The power, which the engine must supply, is the torque (T) times the rotation velocity $2\pi n$ or

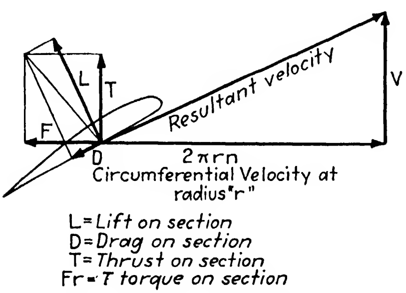


FIG. 124. Forces on propeller section.

$$\text{bhp} = \frac{2\pi n(T)}{550} \qquad (5)$$

n must be the revolutions of the propeller per second. In this manner, propeller absorbs horsepower from the rotating engine shaft and converts it into thrust horsepower.

The propeller diameter, blade width, and blade angle must be so related that the brake horsepower needed is exactly what the engine gives at n revolutions. Tests of propellers are used whenever possible to obtain thrust and power, since calculation by summation of forces on

the sections may be in error because it is impossible to estimate the induced drag and its effects accurately.

Propeller Coefficients. To express the results of propeller tests, coefficients are used. For the thrust, a form similar to that of the lift coefficient is suitable; for the power, an added velocity factor is needed,

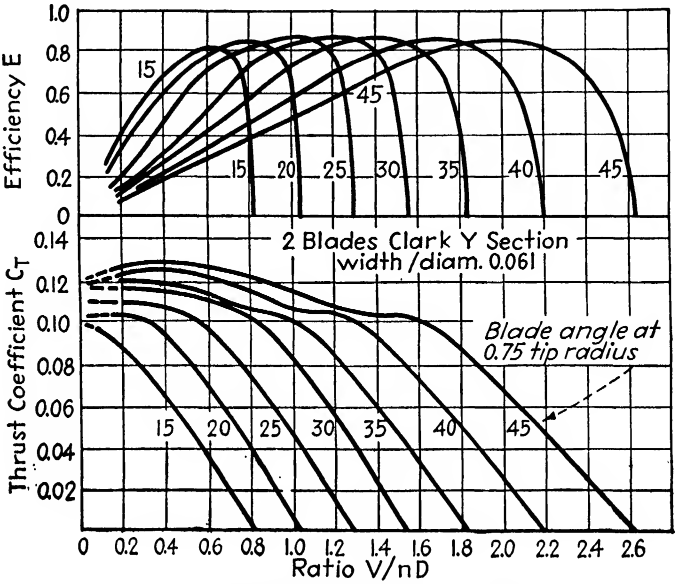


FIG. 125. Thrust coefficients and efficiency. (*Data from NACA.*)

since power is force times velocity. The expressions used are

$$\text{Thrust coefficient } C_T = \frac{\text{thrust (lb)}}{0.202 q_t D^2} \qquad (6)$$

$$\text{Power coefficient } C_p = \frac{\text{bhp} \times 550 \times 32.2}{d n^3 D^5} \qquad (7)$$

where D = propeller diameter, ft
q_t = dynamic pressure corresponding to tangential speed at tip
d = density of air, lb per cu ft
n = rps of propeller speed

A convenient reference for airfoil tests was seen to be the angle of attack. The angle of the sections of a given propeller is fixed by the path angle, which in turn depends on the ratio of forward speed to tangential speed at the tip. It is convenient to use this ratio, or more often π times it, or V/nD, as a reference for the propeller-test results. The variation of thrust and power coefficients with blade angle and

V/nD for a family of metal propellers is shown in Figs. 125 and 126. In Fig. 125 the efficiencies are included. If the resultant velocity of the tip of the propeller is high, more than 1,000 ft per sec, or 650 mph, approaching the velocity of sound, the efficiencies will be reduced below that shown on the figure. Similar curves for wooden propellers would not be greatly different except that the efficiencies would be 3 to 6 per

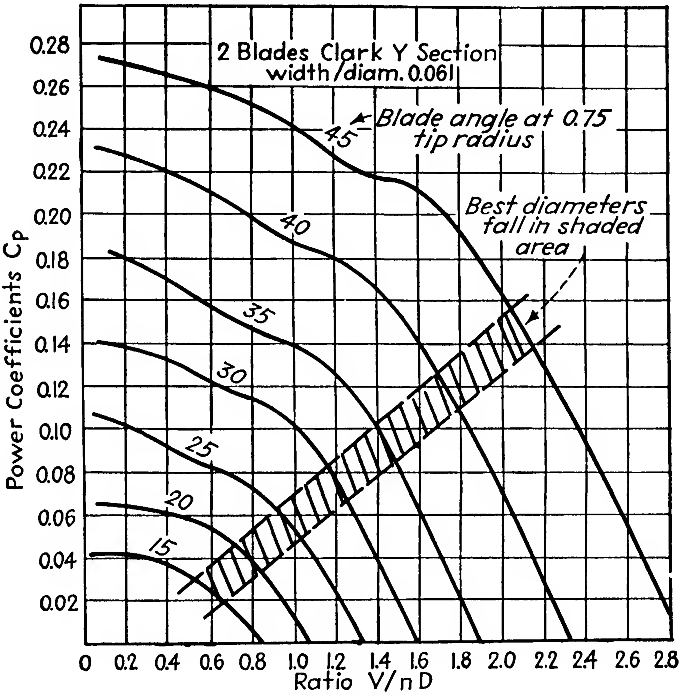


FIG. 126. Power coefficients. (*Data from NACA.*)

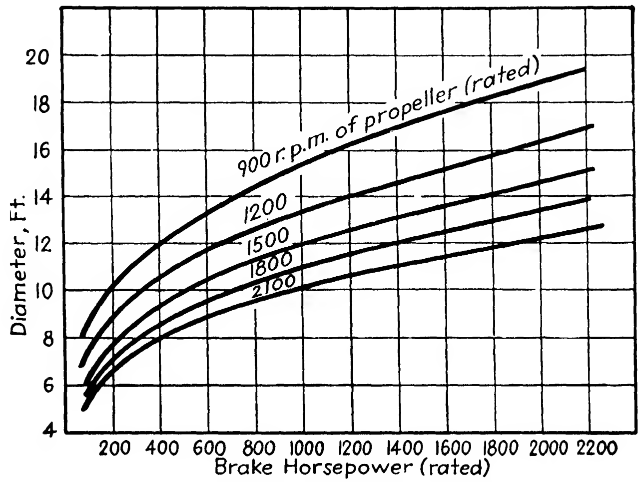
cent lower. Why? Because the wooden propeller is thicker, and the thick sections have more profile drag.

Propeller Characteristics. The propeller diameter is often limited by the necessity of allowing proper clearance between the tips and some part of the airplane. To have a propeller stiff and strong, the blades must not be too narrow or too thin. The tip speed must not be too high. These factors may limit the desirable diameter; otherwise the largest diameter is best, since the ideal efficiency is largest for the largest propeller. Satisfactory diameters for two-bladed propellers of average form are given in Fig. 127. If the diameter and blade shape have been chosen, then the blade angle or pitch must be such that in

level flight at *rated* altitude, the engine with throttle wide open can turn the propeller at just the allowable revolutions. The "rated" altitude and allowable revolutions may be for full power or cruising.

A fixed-pitch propeller is one whose blade angles cannot be changed during flight; they may be adjustable on the ground.

Suppose a fixed-pitch propeller turns n rps in level flight; the pilot pulls back the elevator control, making the plane fly at a lower V; he



Diameters of two-bladed propellers at 200 m.p.h. at sea level.

		Approximate corrections, %
Speed	100 m.p.h.	+33
	300 m.p.h.	−13
	400 m.p.h.	−19
Altitude	10,000 ft.	+7
	20,000 ft.	+15
	30,000 ft.	+22
Blades,	Three	−8
	Four	−14

$N \times D$ should not exceed 16,000. Do not use two blades over 12 ft. in diameter.

FIG. 127. Diameters for two-bladed propellers of average form.

does not close the throttle. The V/nD is lowered. From Figs. 125 and 126, it is seen that the thrust and power coefficients at fixed blade angle increase as V/nD decreases; thus both the thrust and power are increased at constant revolutions. But the engine is already giving to the propeller the maximum power it can; it cannot give more. The result is that the propeller slows down. The reduction in rpm lowers the brake horsepower of the engine; at lower V/nD, the propeller efficiency is lower; the thrust horsepower falls off, since it is the product of brake horsepower and E.

Figure 128 shows a typical relation between rpm and thrust horsepower as V is reduced with a fixed-pitch propeller, with throttle wide

open. If, instead of varying V with throttle open, the pilot closes the throttle as V is reduced, to maintain level flight, the V/nD remains nearly constant. The power coefficient stays the same, and the brake horsepower taken from the engine varies as n^3 and is called the *propeller-load* power.

Figure 125 shows that at the higher blade angles the value of the maximum efficiency is large. To obtain these high values, V/nD must be large, or n should be low. But the engine power varies directly as n; hence, to obtain a large power from a small engine and save weight, n should be high. If the blade angle found for a propeller is less than 15 or 16°, or if the tip speed is high, it will usually be advantageous to have the propeller rpm less than the engine rpm by placing a reduction gear between crankshaft and propeller shaft. This gear may reduce the revolutions in ratios such as 16:11, 3:2, 16:9, 2:0, or 16:7. As the reduction is increased, the efficiency increases; but to offset this gain, the propeller diameter (hence weight and cost) must be increased, and the weight and cost of the engine are increased. The percentage of increase in diameter is less than the percentage of reduction in rpm; hence, the tip speed is less with geared than with direct-drive propellers.

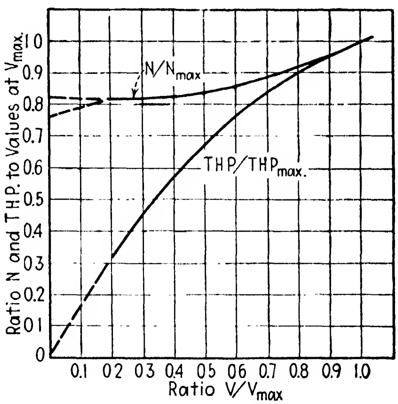


FIG. 128. Average variation of full throttle rpm and thrust horsepower with forward speed for fixed-angle metal propellers.

Propellers with two blades are lighter, more efficient, less expensive, and easier to handle than those with more blades. Three blades, if metal, four if wood, may be used if the space is limited or if the two-bladed propeller would have excessive tip speed. A three-bladed propeller will run more smoothly on a geared engine, and is often used in such a case. Propellers similar to those of Fig. 125 and 126, but with three blades of same diameter and blade angles, would absorb about 43 per cent more power, give 38 per cent more thrust, and be 3 or 4 per cent less efficient at the same V/nD. The diameter would be about 8 per cent less to absorb the same power; the actual loss in efficiency at the same power would be 2 or 3 per cent. For a propeller with four blades of this shape absorbing the same power, the diameter would be about

14 per cent less, the efficiency 3 or 4 per cent less than for the two-bladed propeller.

Sometimes, when the diameter is limited, extra-wide blades may be used. The power needed by the propeller increases directly as the blade width, and up to 25 per cent increase in width, there is not over 1 per cent reduction in efficiency. Of a geometrically similar family of propellers, one of a certain blade angle will give the best efficiency and the highest speed (with fixed N and horsepower). Somewhat steeper climb and shorter take-off run would be attained by reducing the blade angle 3 or 4° and increasing the diameter 10 per cent. The maximum speed with such a propeller will be lower, but this sacrifice may be warranted on training planes, flying boats, or other types with slow take-off.

Controllable-angle Propeller. From Fig. 128 it is seen that at low forward speeds, a fixed-angle propeller which is suitable for level flight conditions allows the engine to develop only 75 or 80 per cent of its full power. At very low forward speed, the efficiency of propellers with large blade angle is much less than that of those with low angle. At any given density, the power coefficient with the engine operating at full power and revolutions is independent of the velocity

$$(\text{bhp} = C_P \times 0.0000565dn^3D^5),$$

while V/nD varies directly as the velocity. The curves in Fig. 126 show how the blade angle must vary with velocity to keep C_P constant as V varies. During take-off, the advantage of the controllable-blade-angle propeller is twofold: it permits the engine output to remain at its maximum allowable value and is more efficient. During climb at moderate flight speeds, only the advantage of utilizing the full engine power is realized, since the efficiency would differ but little from that of the fixed-angle propeller.

As we have already learned, the power given by the engine falls off at altitude. The rate of decrease is somewhat faster than the rate of decrease of air density. To avoid this loss in power, all large engines are now fitted with superchargers, which allow the engine to develop substantially constant power up to the critical altitude. The power needed by the propeller at any V/nD varies directly as the air density, so the propeller demands at altitude a little more power than the unsupercharged engine can supply. Therefore, the full-throttle revolutions decrease slightly as the altitude increases. A reduction in blade angle in flight at altitude would avoid this decrease and give more power. With the supercharged engine, the opposite is true. The propeller

must be large enough to absorb all the engine power in level flight at the critical altitude. Below that altitude, the power needed by the propeller increases as the density increases, but the engine can give no more power; thus again a fixed-angle propeller would slow down the engine, seriously, if the critical altitude is high. The remedy is to reduce the propeller blade angle, in this case at low altitudes.

Propellers whose blade angle may be varied in flight are called *controllable propellers, controllable-angle propellers,* or *controllable-pitch propellers.* In such a propeller, the entire blade is rotated in a bearing in the hub. Sometimes the blade may be set at any desired angle, so that the engine may give full revolutions for full power or, alternatively, cruising revolutions for cruising power under all flight conditions. The angle may be controlled by the pilot, or it may be controlled by a governor; in the latter case it is a *constant-speed propeller;* the pilot can adjust the revolutions which the governor keeps constant. Sometimes, to simplify the mechanism, the propeller is made so that there are only two positions: high pitch for level flight, and low pitch for take-off and slow climbing velocities. Such propellers were the first controllables extensively used but have been replaced on large or high-powered airplanes by constant-speed ones as cruising speeds and altitudes have increased.

The controllable propeller does not increase materially the maximum speed at rated altitude or the cruising speed at best cruising altitude (the altitude where full-throttle operation does not exceed the cruising-revolution limit, power limit, or manifold pressure limit, usually about 5,000 ft above the rated altitude). It does, however, allow the potential engine power to be more effectively utilized at other speeds and altitudes.

With a two-position propeller the maximum blade-angle change is about 20°; the constant-speed type may allow 50° change for normal flying, *i.e.*, from take-off to cruising at altitude. A *feathering* or *full-feathering* propeller is one that permits the blade angle of the propeller on an idle engine to be increased to nearly 90°; it will then stop rotating and offer the lowest possible drag. This is a very important advantage for flight of multi-engine airplanes with one engine stopped. When the first experimental controllable propellers were made, they were often *reversible, i.e.*, the blade angle could be made negative; thus, using part engine power, a negative thrust could be obtained. The object was to use the propeller as a brake to shorten the run of the airplane after landing. The development of brakes for airplane wheels provided a more convenient stopping force, and the use of reversible propellers ceased.

Later as the weight and landing speed of airplanes have become large, provision of adequate mechanical brakes has become so difficult that many transports and bombers have reversible-thrust propellers. These provide a larger retarding force than brakes, particularly imme-

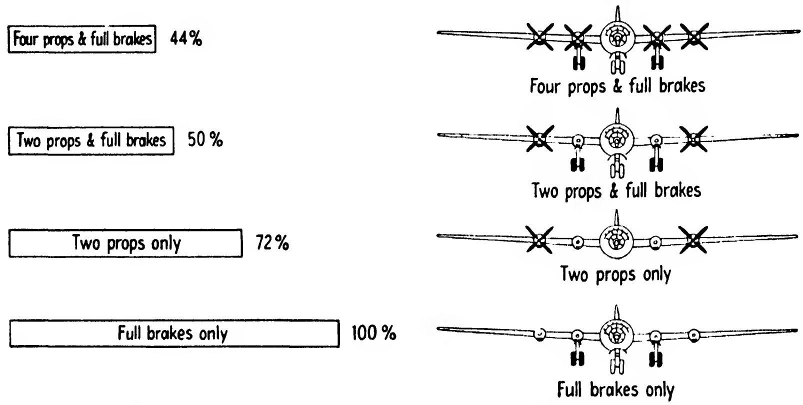


FIG. 129. Effect of reversible-pitch propellers on landing distance. (*Curtiss Propeller Division.*)

diately after the wheels touch the runway (Fig. 129). Reversible propellers have also been used to assist in stopping and maneuvering four-engine flying boats on the water. The blade angle of the inboard propellers is set to give negative thrust, that of the outboard to give positive thrust when the throttles are opened (Fig. 130). To prevent a rapid rise in revolutions, the throttle must be closed tight while the propeller is being reversed. Since the negative angle desired may be about 25°, a total change range of 115° is needed for a reversible, full-feathering propeller.

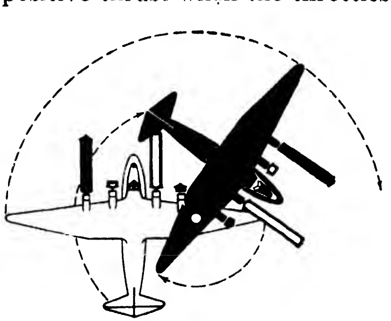


FIG. 130. Turning flying boat with reversible-pitch propellers. (*Curtiss Propeller Division.*)

Propeller Construction. For many years, most airplane propellers were made of wood, and while metal is now the preferred material for propellers to be used on engines of 300 hp and more, the relative cheapness of wooden propellers still gives them the advantage in small sizes. Of the many species of wood that have been tried for propellers, birch is considered to be the best. A wooden propeller is not carved from a single piece but is built up of several separate planks,

or *laminations*, each of which, in a two-bladed propeller, extends from tip to tip. The individual laminations are cut roughly to shape and glued together. The propeller is then roughly shaped, often by machine, and afterward is carefully finished by hand. During this process it is approximately balanced. The tips and the leading edges of the blades are covered with a thin metal sheathing, which is attached to the blade by means of countersunk wood screws. This tipping is useful to protect the most exposed parts of the blade from the action of the weather and also from the abrasive effect of dust or pebbles, which

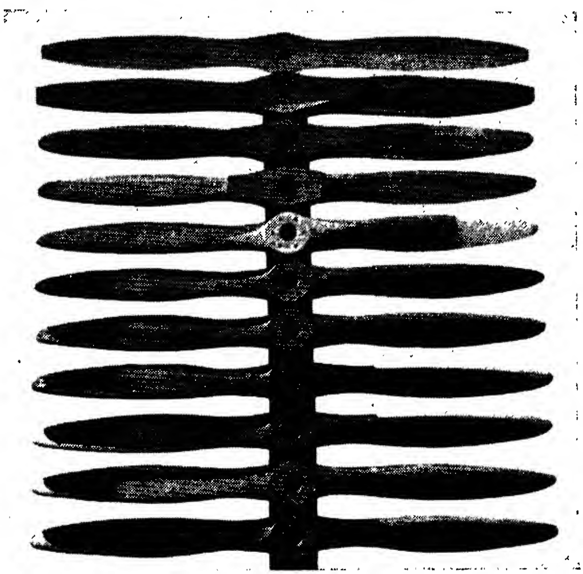
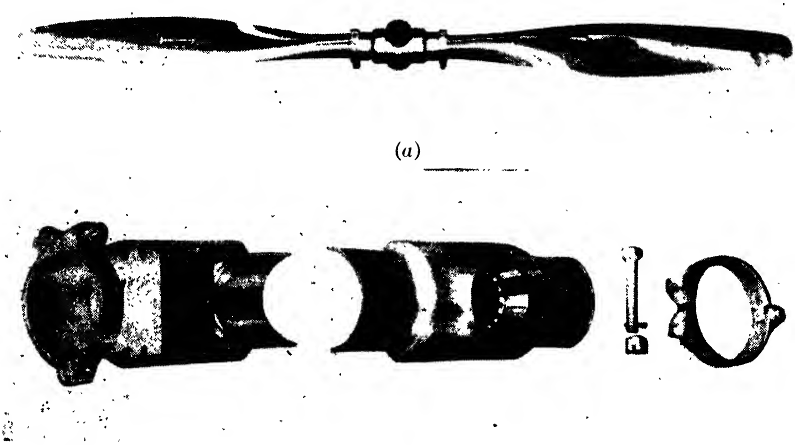


FIG. 131. Steps in manufacture of wooden propellers. (*Sensenich Brothers.*)

may be picked up while the propeller is running on the ground. Finally, it is mounted on a spindle and is very carefully balanced. Steps in the manufacture are shown in Fig. 131.

To increase the serviceability of wooden propellers and make possible their use on high-power engines, several methods of increasing their surface hardness, resistance to moisture, and strength have been developed. The essential features are: an extra-light blade section of laminated spruce with each lamination scarfed to one of heavy, compressed, wood plastic, forming the root section; for controllable propellers, the root section screwed into a steel ferrule; a plastic cover over the entire blade, reinforced with linen or steel gauze "baked" in place, thus forming a tough weatherproof surface; a heavy metal leading

edge to resist abrasion of stones, water, etc. The finished blade complete with ferrule weighs about half as much as a solid aluminum-alloy blade for the same propeller and need be little (if any) thicker, particularly at the vital tip sections.



(b)

FIG. 132. The Hamilton Standard propeller: (a) complete propeller, (b) parts of hub. (*Hamilton Standard Propellers.*)

Most propellers used on engines of more than 300 hp are metal; almost all have controllable blade angle. One type of fixed-angle (during any one flight) propeller is the Hamilton Standard, which is shown in Fig. 132. Each blade consists of a single piece of duralumin forged into the proper shape and finished to exact size. The butt of the blade fits into a socket in the hub, and two shoulders prevent it from coming

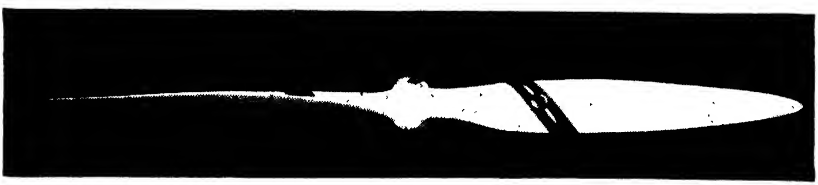


FIG. 133. Curtiss one piece propeller. (*Curtiss Aeroplane and Motor Co., Inc.*)

out. All surfaces of hub and blade must be highly polished, even though the task is difficult for some parts of the inside of the hub, since otherwise the small scratches of a rough surface might lead to cracks and propeller failure. With this construction, the angle of the blades may be readily changed simply by turning them in their sockets

after the clamps have been loosened. The weight of this propeller is more than that of a corresponding wooden propeller.

Another type of metal propeller is the Curtiss, shown on Fig. 133. The whole propeller is forged from a single piece of duralumin. The hub is smaller than that of the Hamilton Standard propeller but does not permit a change in blade angle, except by twisting the blades. The weight of the complete propeller is somewhat more than that of a corresponding wooden propeller.

A steel propeller is better able to withstand abrasion of rain, cinders, etc., than a duralumin one. In order to be light, yet rigid, it must be hollow. One example, originated by Dicks, developed and widely

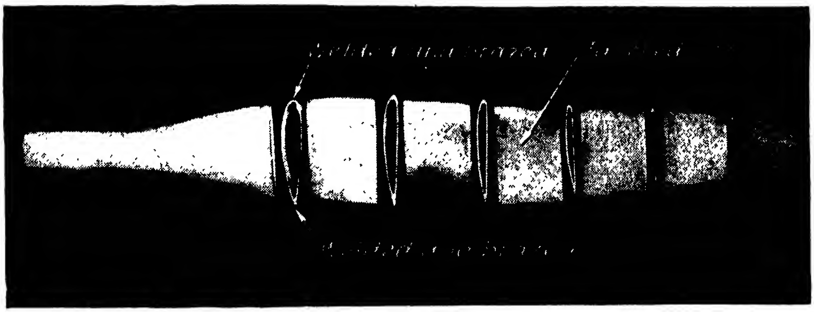


FIG. 134. Hollow steel propeller blade. (*Curtiss Propeller Division.*)

used by the Curtiss Propeller Division for the controllable propellers, shown on Fig. 134, is formed of two tapered sheets of chrome-vanadium steel welded and brazed together along the leading and trailing edges.

Controllable-propeller Construction. Most controllable-angle propellers have blades of metal, either duralumin or hollow steel. The first problem to be solved is to hold the blade rigidly, at the same time permitting it to be rotated easily in the hub to change the angle. The centrifugal pull on a large blade at high tip speed may be 150,000 lb (the weight of a cube of steel 7 ft on each edge)! This load may be carried by a *roller thrust bearing* with a plain bearing for side support (Fig. 154) or by a series of *stacked ball bearings* that also offer side support (Fig. 143).

The second problem is to devise a method for controlling or setting the blade angle while the propeller is rotating. There are several basic methods: mechanical gearing from the propeller shaft or an electric motor on the engine, electric motor on the hub turning blades through a reduction gear, hydraulic cylinder linked or geared to the blades. In a few types the blade is mounted so that it changes angle automatically.

Hamilton Standard Controllable Propellers. The controllable-angle propeller which was first extensively adopted was the hydraulic two-position propeller made by Hamilton Standard Propellers, Division of United Aircraft Corporation. In this type, engine oil pressure admitted to a cylinder in the hub by a valve operated by the pilot forced the propeller into low pitch; release allowed counterweights to rotate the blades to high pitch. Addition of a simple spring-loaded

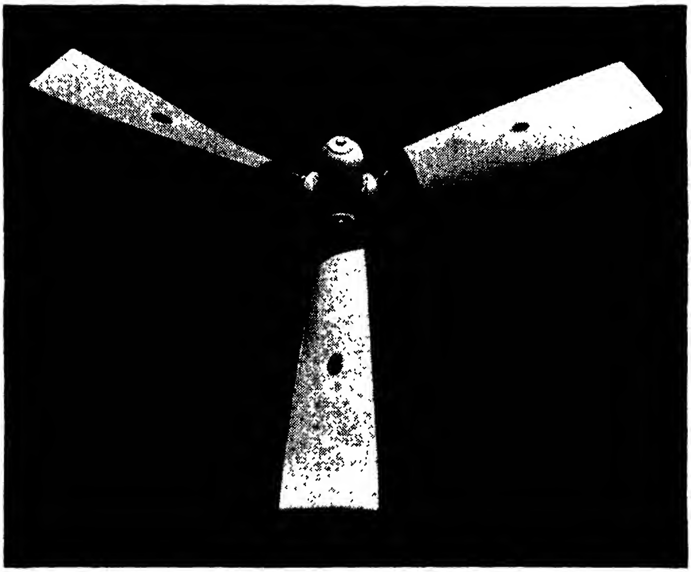


FIG. 135. Reversing Hydromatic propeller. (*Hamilton Standard Propellers.*)

centrifugal governor, replacing the pilot as operator of the valve, changed the propeller into the constant-speed type. As the desired angle changes increased, a new principle, in which the axial motion of the hydraulic piston turned a gear meshed with sectors on the blades by means of spiral slots in cams, was introduced in the *Hydromatic* propeller. (The action is similar to that of the Yankee push-screw driver.) In addition, in case of engine trouble, the blade angles of the Hydromatic could be increased to about 90° or feathered, stopping the rotation of the propeller and reducing the drag of the blades to a minimum. Over half a million propellers of these three types have been built by Hamilton Standard Propellers and licensees. All had forged aluminum-alloy blades. These types, two-position, constant-speed, and Hydromatic, have been considered in some detail in earlier editions of this book.

To add the desirable feature of obtaining a negative thrust by reversing the angle of the blades, a simple extension of the cam slots of a Hydromatic propeller would appear to suffice, but control of the procedure requires more complicated oil-transfer arrangements. Hence

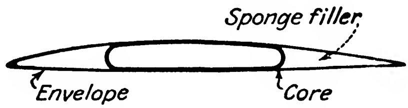


FIG. 136. Section of steel blade. (*Hamilton Standard Propellers.*)

the *Reversing Hydromatic* incorporates radical changes to provide for reversing. Simultaneously the redesign permits the incorporation of improvements in the hub and blades. The Reversing Hydromatic (Fig. 135) has hollow steel blades, with a single-piece steel hub. The blades have a flattened tubular core of high-strength steel that also forms the

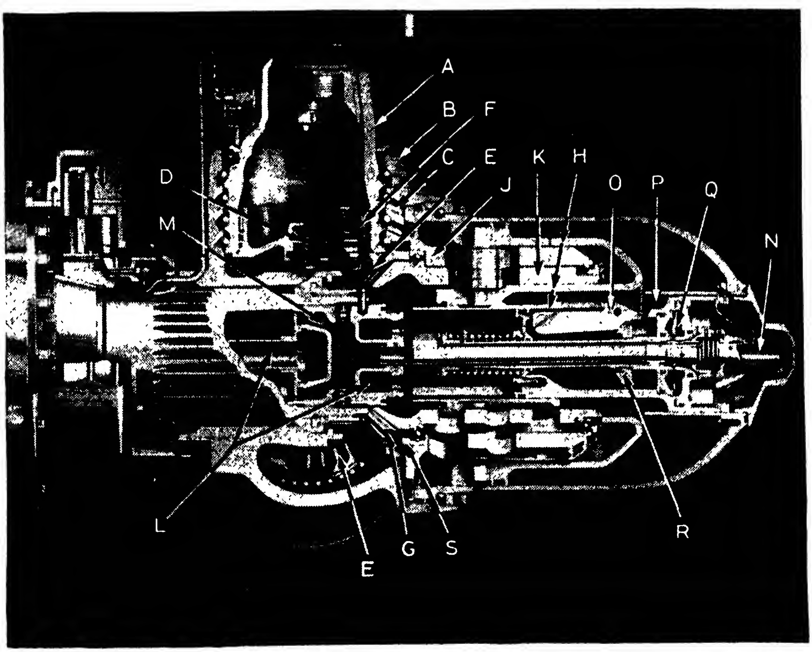


FIG. 137. Cutaway of Reversing Hydromatic hub. (*Hamilton Standard Propellers.*)

root. Around this core is brazed a thin alloy cover or envelope forming the airfoil contour of the blade (Fig. 136). The envelope extends down to the propeller spinner, providing better airfoil sections on the inner portion of the blade than could be obtained on aluminum-alloy

blades without fitting of extra cuffs. By using a special hardening process, ball-bearing races for retaining blade in hub are ground directly on the blade core itself. The outer races for the ball bearings are ground in similarly hardened sections of the hub barrels (Fig. 137, *A* and *B*). By slipping the blade in too far, balls can be fed into the races through slots *C*. The blade is then jacked out into proper position (as shown) by the preloading screw *D* that pushes against the hub itself, thus locking the blades in place. Into the hollow blade end fits the blade sector *E*, which turns the blade through a splined ring *F*. This ring also allows fine adjustment of angle between sector and blade. On the blade shank just above the hub barrel is a slip ring and brush; through these, current is transmitted to the blade de-icer built into the leading edge, and they also form part of the control circuit for the auxiliary high-pressure oil pump.

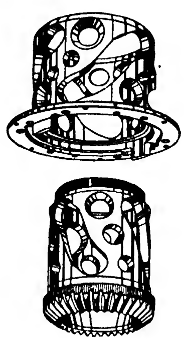


FIG. 138. Slotted cams. (*Hamilton Standard Propellers.*)

Blade angles are fixed by the power gear *G* meshed with the blade sectors. Motion of the peculiarly shaped piston *H* twists the power gear, since the rollers in the piston fit in spiral slots in both fixed cam *J* and moving cam *K* (see also Fig. 138) and the power gear is part of moving cam. In the Reversing Hydromatic, direction of spiral slots is opposite to that of earlier Hydromatics so that the piston travels forward to reduce the angle, and if moved far enough, to reverse the pitch.

The problem is to control the flow of oil so that the piston moves to accomplish desired changes. For normal operation in flight, the Reversing Hydromatic is a constant-rpm propeller. A double-acting centrifugal governor, spring-loaded to maintain rpm desired by pilot, moves a piston valve if rpm are not right, so that the gear pump included in the governor can transfer oil from one side of piston *H* to the other, hence moving the piston and blades to permit the engine to attain desired rpm. Oil flows to and from the governor through two oil-transfer rings on the propeller shaft that lead to separate passages through the shaft, *L* to the rear of the piston, *M* to the front. If rpm are too high, the governor lifts the piston valve; oil flows from the pump through passage *M* and oil tube *N* to the outer side of the piston, pushing the piston back, rotating the blade to higher pitch, slowing the

engine down. For low revolutions the action is reversed (Fig. 139), though less oil pressure is required because the blades by themselves are rotated toward low pitch by centrifugal force. A mechanical stop *O* (Fig. 137) limits the lowest blade angle; this angle is adjusted by turning the low-pitch stop unit in the thread *P*.

When it is desired to obtain negative thrust to slow down the plane after landing, oil must flow through passage *L* and push piston *H* forward. The oil fills the servovalve *Q* through an annular passage around the oil tube *N*. If the oil pressure is high enough, servopiston *Q* is pushed forward, retracting the stop *R*; this allows blade angle stop

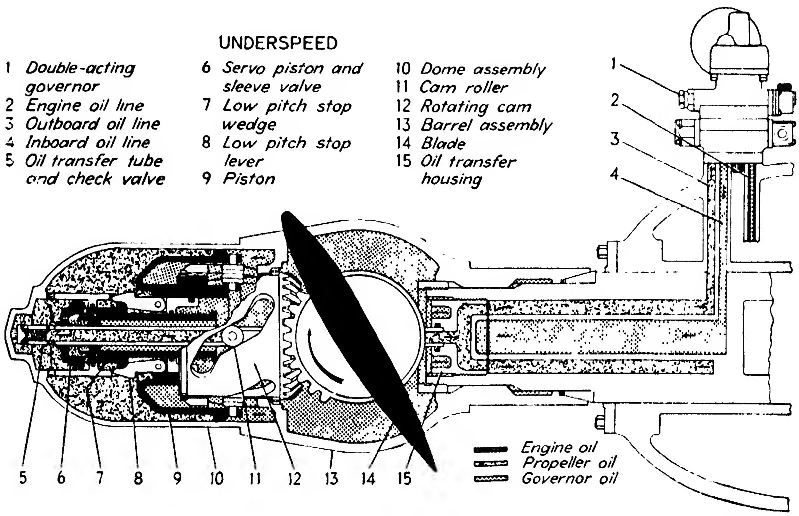


FIG. 139. Schematic diagram of Reversing Hydromatic hub. (*Hamilton Standard Propellers.*)

O to retract; the main piston then moves the blades to the reverse pitch angle (about $-25°$). Propeller is shown reversed on Fig. 140. This angle is fixed by mechanical stops in a ring *S* and fixed cam. This sequence is controlled by the throttle lever. From the closed position with engine idling, the throttle is pulled slightly back, closing a switch that starts an auxiliary high-pressure oil pump driven by an electric motor. The oil from this pump flows through the governor to oil passage *L* and accomplishes the reversing. When reverse angle stop is reached, the oil pressure increases, actuating a switch to stop the high-pressure pump. This entire operation requires only a second or two. Then if the throttle lever is pulled back farther, it opens the throttle, increasing the rpm and the negative thrust. Oil from the governor

pump holds the propeller blades fixed against the reverse-angle stop. The centrifugal governor valve is by-passed by a solenoid-controlled valve.

When negative thrust is no longer needed, the throttle lever is returned to the normal closed position. This restarts the high-pressure oil pump, but the flow is directed through passage *M* to the front of the piston, rotating the blade toward high pitch. The spring on the low-pitch stop unit pulls the servovalve shut, thus resetting the stops as soon as the piston sleeve *H* moves off of them. After blade angle

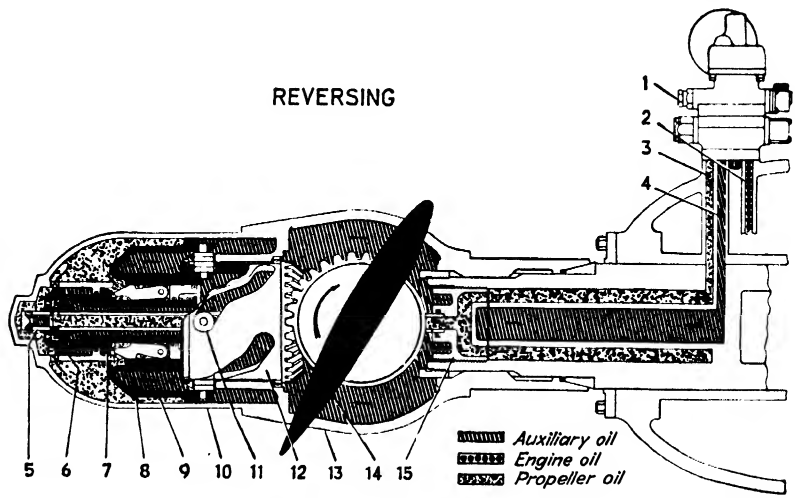


FIG. 140. Schematic diagram of Reversing Hydromatic, propeller reversed. (*Hamilton Standard Propellers.*)

reaches a few degrees above the low-pitch stop setting, current is shut off the auxiliary pump by closing a circuit through the brush and partially insulated slip ring on the blades *A*. Propeller is then ready for normal constant-rpm operation.

To feather the propeller quickly, oil at high pressure and considerable volume is needed. This is supplied by manually closing a "feather" switch, starting the auxiliary high-pressure oil pump. Oil flows through the governor and oil passage *M*, forcing the piston back and the blades to the "feathered" angle, about 85°, at which the engines stop turning. Turning of blades is stopped by a mechanical stop ring *O*. When this occurs, the sudden rise in oil pressure opens a switch, stopping the auxiliary oil pump. The blades remain in feathered position; no pressure is required since the engine is not turning.

If the engine has been feathered for practice, or if the trouble necessi-

tating stopping the engine has been remedied, the propeller is unfeathered by pulling momentarily an "unfeather" button, closing the circuit to start the auxiliary pump and to transfer its oil flow through passage *L* to the back of piston, thus turning blades to a lower angle. If the plane is in flight, the air load on the blades will turn the engine, allowing it to be restarted; when it reaches about 800 rpm, or when the blades are a few degrees below highest constant-rpm blade angle, the auxiliary-oil-pump circuit is automatically opened if the pilot has inadvertently held the button closed. The oil pressure is needed only for a second or so, since the only resistance to turning of blades is the friction; once rotation has started, the blades will be twisted toward low-pitch position by centrifugal force.

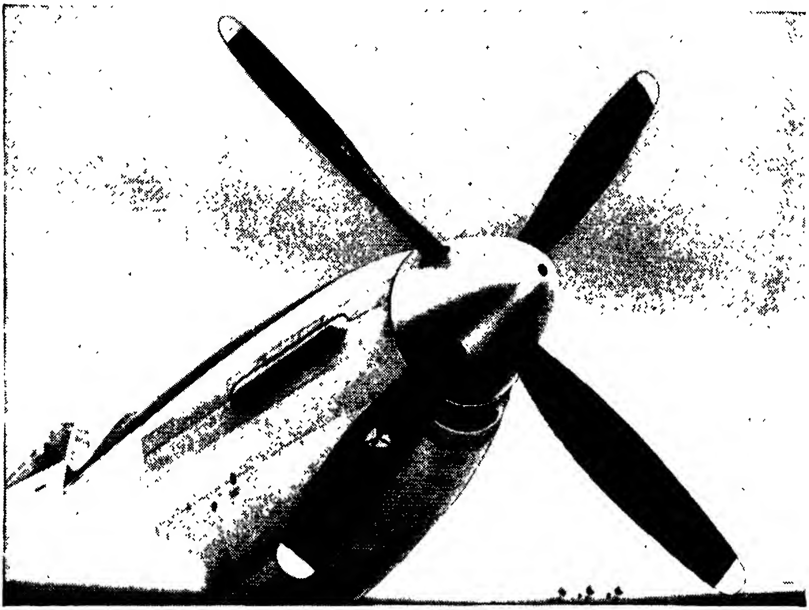


FIG. 141. Aeroproducts propeller. (*Aeroproducts Division.*)

Aeroproducts Controllable Propellers. Another propeller incorporating a selective constant-speed principle is manufactured by Aeroproducts Division of General Motors Corporation (Fig. 141). It also is hydraulically operated, and all parts, including the hydraulic pump and governor, are contained within the propeller, thus making the hydraulic system independent of the engine oil system.

The blades are of hollow steel construction, with a longitudinal strengthening rib (Fig. 142). It is assembled of a thrust member 4

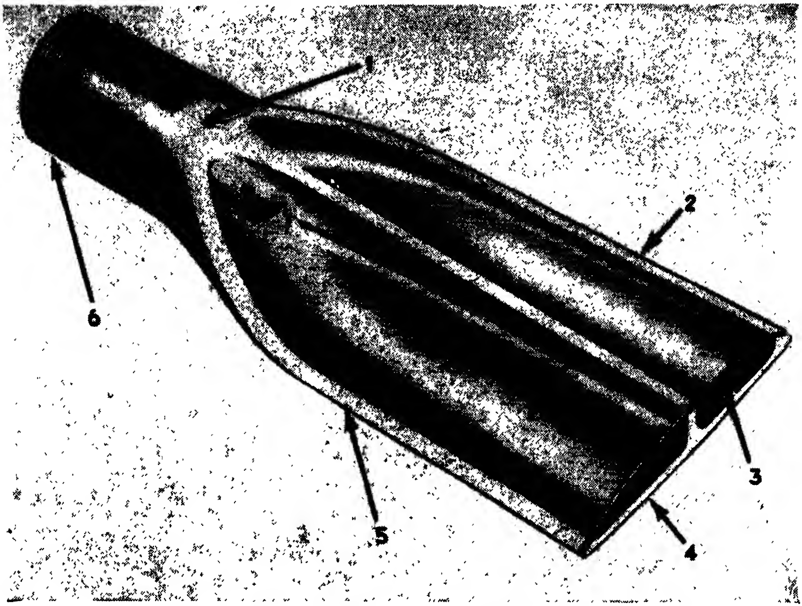


FIG. 142. Hollow steel blade. (*Aeroproducts Division.*)

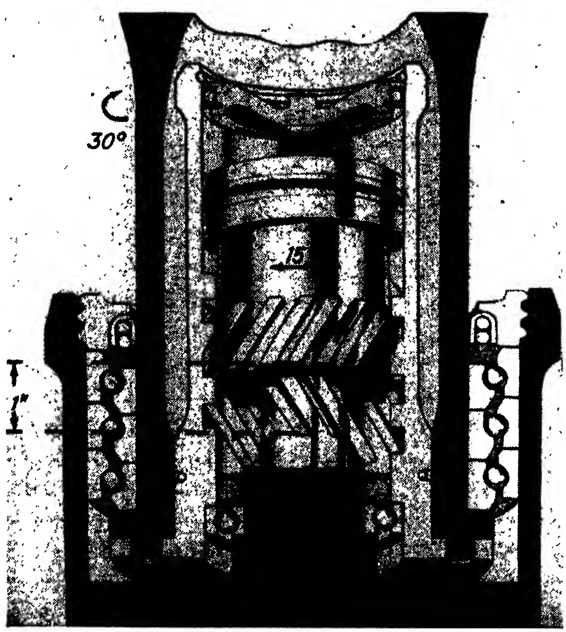


FIG. 143. Schematic sketch of blade root and torque units. (*Aeroproducts Division.*)

and a camber sheet 3, which are brazed together. The thrust member is a polished steel forging forming the thrust face, longitudinal rib, and leading- and trailing-edge reinforcements 2 and 5. It extends inward to form the root 6. Blades are held in the hub by preloaded ball bearings and a retaining nut that is screwed into the hub socket, as schematically illustrated in Fig. 143.

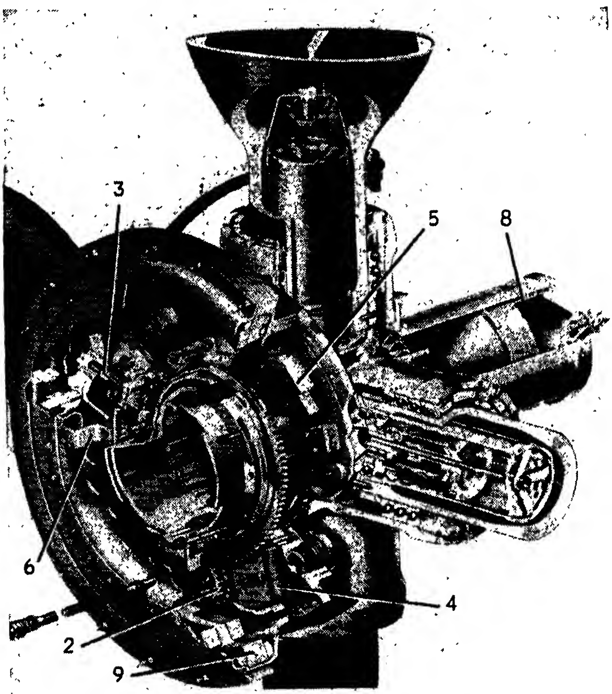


FIG. 144. Cutaway view of hub. (*Aeroproducts Division.*)

Figure 143 also illustrates the principle by which the blade angle is changed. The application of hydraulic pressure to either side of the torque piston (marked 15°) will give it axial movement along a spirally splined stem that is bolted to the hub, hence will twist the piston. Since external splines on the piston engage mating splines in the torque cylinder, to which the propeller blades are doweled, moving and rotating the piston also rotates the cylinder and changes the blade angle. A 1-in. axial movement of the piston will turn the piston 15° and the blade 30°. A *torque-unit* assembly is incorporated in each blade socket of the hub. The hub is shown cutaway in Fig. 144 and schematically in Fig. 145.

The hydraulic fluid necessary to change the blade angle is contained in a regulator unit 1 attached to the propeller hub and rotating with it. This provides a self-contained hydraulic system which is entirely independent of the engine or any other oil system. The regulator unit contains a gear-type pump 2 to create the necessary hydraulic pressure, a governor 3 to distribute the hydraulic fluid to the torque units, a pres-

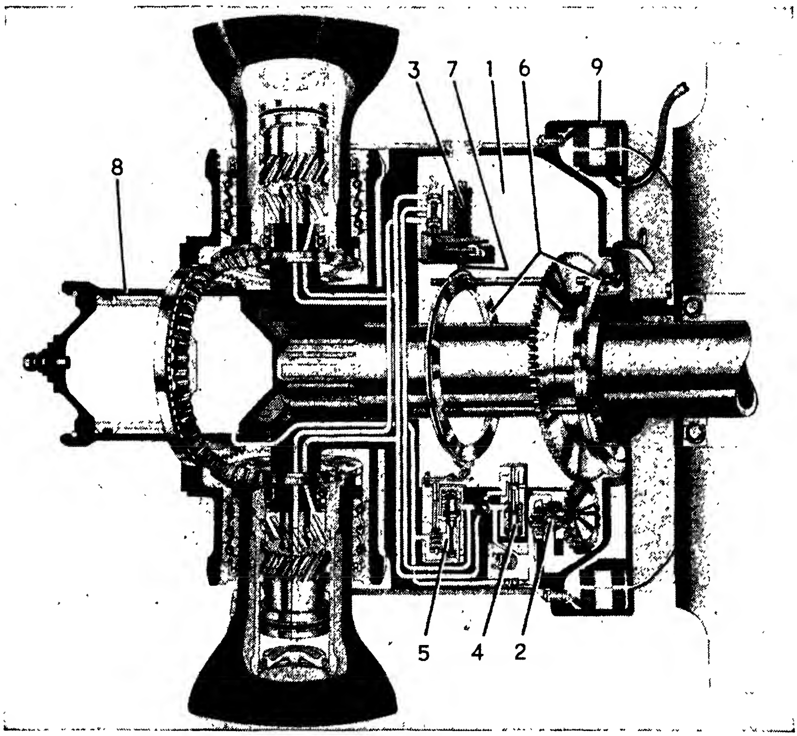


FIG. 145. Schematic sketch of hub. (*Aeroproducts Division.*)

sure control valve 4 to limit the maximum operating pressure while allowing adequate pressure for all operating conditions, a feathering valve 5 to direct the flow of hydraulic fluid during the feathering and unfeathering operations, and a control mechanism 6 to permit the pilot to set the governor manually and to feather and unfeather the propeller. The control assembly is prevented from rotating by a bracket to the engine crankcase.

The centrifugal governor 3 (see also Fig. 146) automatically distributes hydraulic fluid to the torque units as required. Since the regulator unit rotates with the propeller, centrifugal force moves the governor

piston A outward, compressing the governor spring B through lever C. Therefore, the position of the governor piston depends upon the centrifugal force acting upon it, the force of the spring, and the position of the movable fulcrum D. As shown in Fig. 146, piston is in "on-speed" postion, indicating that propeller is turning at the rate desired by the

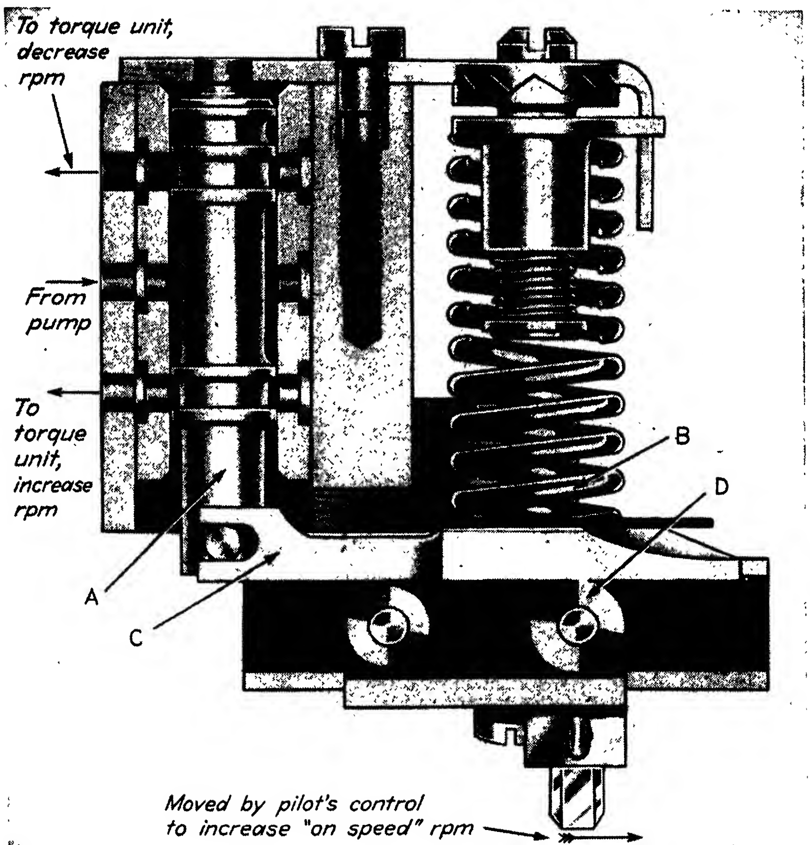


FIG. 146. Centrifugal governor ("on speed"). (*Aeroproducts Division.*)

pilot, and allowing no fluid to flow from pump to torque units. The movable governor fulcrum provides a method of changing the amount of centrifugal force necessary to overcome the spring force. If the fulcrum is moved nearer to the spring, less centrifugal force is required to balance the spring force; hence the piston will be "on speed" at lower rpm. If the fulcrum is moved farther from the spring, "on-speed"

rpm are increased. If rpm varies from desired "on-speed" value, the centrifugal force on the piston, varying as $(\text{rpm})^2$, no longer balances the spring force, and the piston moves out if rpm are high, in, if rpm are low, allowing fluid from the pump to flow to the torque units. The outer pipe, uncovered if rpm are high, leads to the inboard end of torque cylinders; the fluid forces the piston outward, increasing blade angle, hence propeller torque. Increase of torque slows engine immediately to "on-speed" rpm. If rpm is low, sequence is reversed, blade angle decreased, and engine returns to "on-speed" rpm.

The pilot selects the engine rpm by moving the cockpit control 6 (Fig. 145), which in turn rotates the propeller control lever. This control lever is integral with a ring gear having teeth on its internal edge. These internal teeth mesh with three small pinions which form the heads of control screws. The control lever rotates the control screws, which transmit a fore-and-aft movement to the control ring. A groove in the control ring engages a shoe 7 on the governor carriage, changing the position of the fulcrum. (The control ring does not rotate, while the shoe rotates with the regulator.)

For feathering and unfeathering the propeller, a positive source of pressure is necessary, since pressure from the pump in the regulator is developed only while the propeller is rotating. This source is an accumulator cylinder 8 (Fig. 145), in which a piston separates compressed nitrogen gas on one side from hydraulic fluid on the other. Feathering the propeller is accomplished by moving the propeller control in the cockpit to the feathering position, moving the control ring far forward. This moves the fulcrum very close to the spring, allowing the piston to move out and also actuates the feathering valve, permitting fluid to flow from the accumulator through the governor to the inner ends of the torque-unit cylinders, feathering the propeller almost instantly. Only a portion of the hydraulic fluid in the accumulator is used for the feathering operation. If the propeller control is moved back to the operating position, the governor piston moves inward to the decrease-blade-angle position; the feathering valve is again actuated, and the hydraulic fluid from the accumulator is directed through the governor to the outboard side of the torque-unit pistons, unfeathering the propeller. When the propeller has been unfeathered and is operating, the accumulator is automatically recharged with hydraulic fluid, ready for the next feathering cycle if it should ever be needed. No nitrogen gas is lost.

One propeller model incorporates an electric generator 9 (Figs. 144 and 145) to provide current for electric heating shoes on the leading

edges of the blades. These are heated to remove ice formation from the propeller blades.

Curtiss Electric Propellers. Many propellers with blade angle controlled by an electric motor have been built by the Propeller Division of the Curtiss-Wright Corporation (Fig. 147). These propellers usually have hollow steel blades (Fig. 134). The hub is a single-piece steel forging with blades supported by stacked ball bearings, preloaded to ensure proper positioning (Fig. 149).

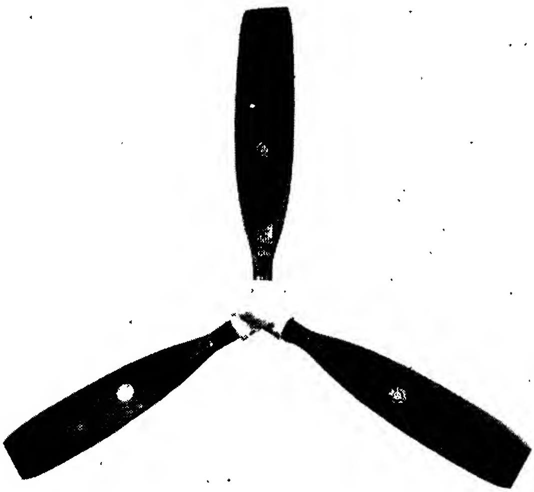


FIG. 147. Curtiss electric propeller. *(Curtiss Propeller Division.)*

Controlling the blade angle by an electric motor is basically very simple, but if it is desired to feather and reverse the propeller in addition to maintaining constant engine rpm automatically, the electrical system becomes complex (Fig. 148). The motor *A* (Fig. 149) drives the power gear *C* through a double planetary gear reduction *B*. The planetary reduction gear is the type often used on radial engines, but the reduction is much larger, several thousand motor revolutions to one of the power gear, thus enabling a small motor to produce sufficient torque to move the blade. The power gear is meshed with a sector *D* on each blade. The pitch-change motor has two separate fields, opposed in direction, hence it may be reversed merely by energizing one or the other field. At the end of the motor is a powerful spring-applied brake *E*. The motor current passes through a solenoid that releases the brake. As soon as any switch is opened in the motor cir-

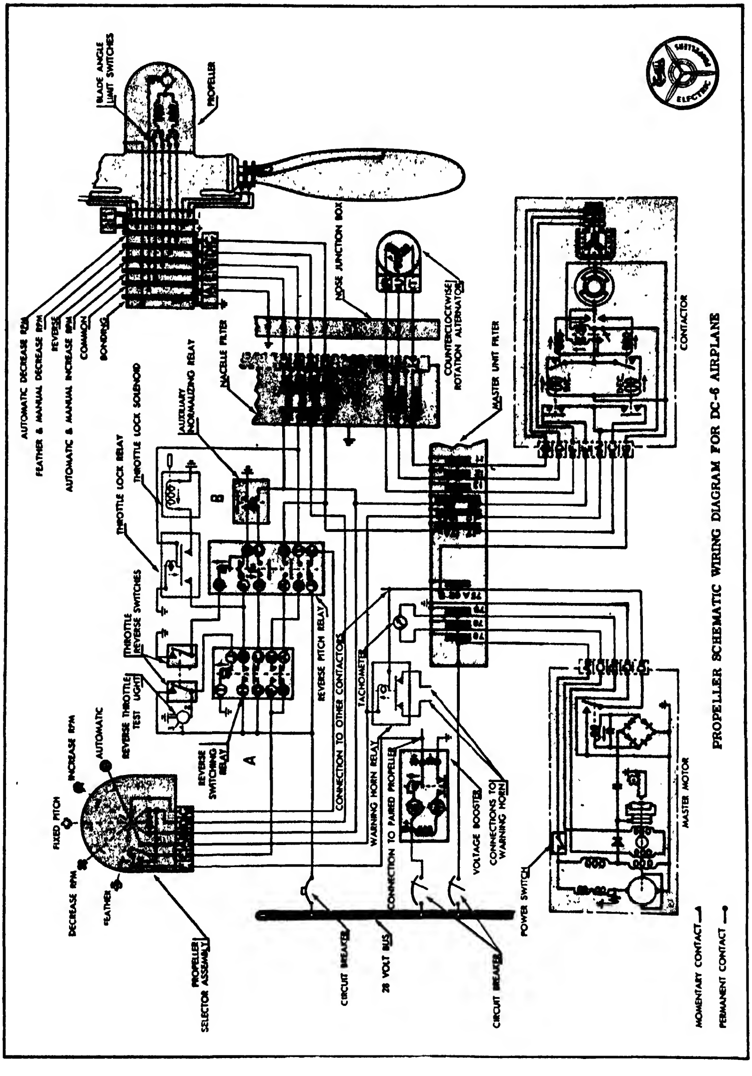


FIG. 148. Propeller schematic wiring diagram. (*Curtiss Propeller Division.*)

cuit, the brake clamps the motor, thus holding the blade angle. Fastened to the power gear is a cam F that opens or closes limit switches that fix the highest and lowest normal blade angle, the feathered angle, and the reversed-thrust angle. These are necessary to prevent undesirable blade angles and possible danger to propeller or plane. The motor receives current from the airplane electrical system through slip rings G and brushes. In order that the limit switches may be in their proper circuits, four separate circuits are required: two that increase

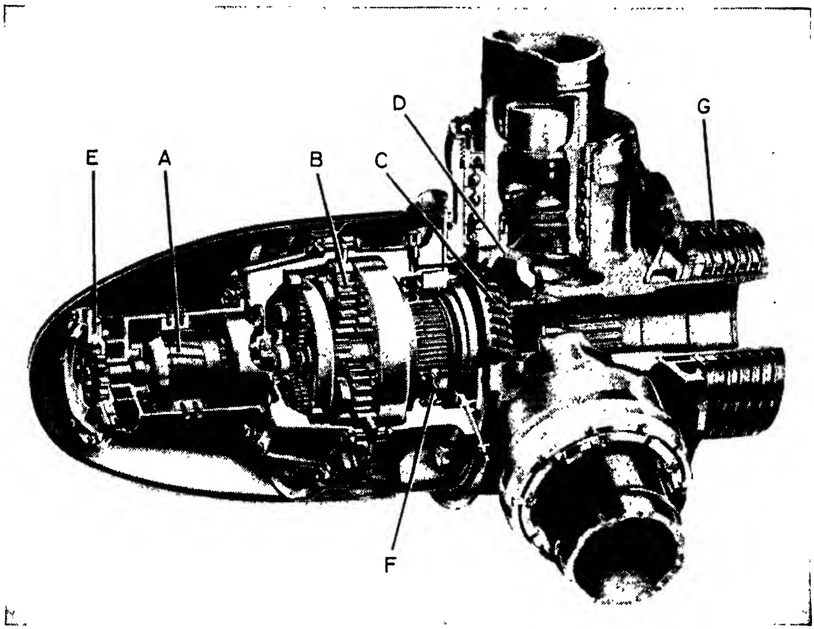


FIG. 149. Cutaway of Curtiss electric propeller hub. (*Curtiss Propeller Division.*)

the blade angle, hence causing a reduction in the propeller revolutions, and two more that reduce the blade angle. These are labeled on the schematic wiring diagram (Fig. 148).

In the cockpit there are three controls for the propellers: one *selector* (Fig. 150, for four propellers) permitting the pilot to operate any one propeller as a fixed-pitch propeller, as a manually operated propeller, or as an automatically controllable propeller, or in case of emergency to feather it; one *rpm-control quadrant* that adjusts the revolutions of the master motor during automatic-control operation (most of the time the plane is in the air); and *switches* for reversing the thrust, operated by the throttle lever of each engine.

Before any propeller can be feathered, a push button on the selector must be released. Then moving the lever to "feather" connects the booster armature line to the feather brush, hence to the pitch-change motor. As soon as this circuit is closed, the solenoid switch in the *booster* is closed, starting the booster. This booster is a combination motor and generator on a single shaft used to increase temporarily the volts and power of the pitch-change motor. Its use decreases feathering time to less than 10 sec. The selector feather switch remains on;

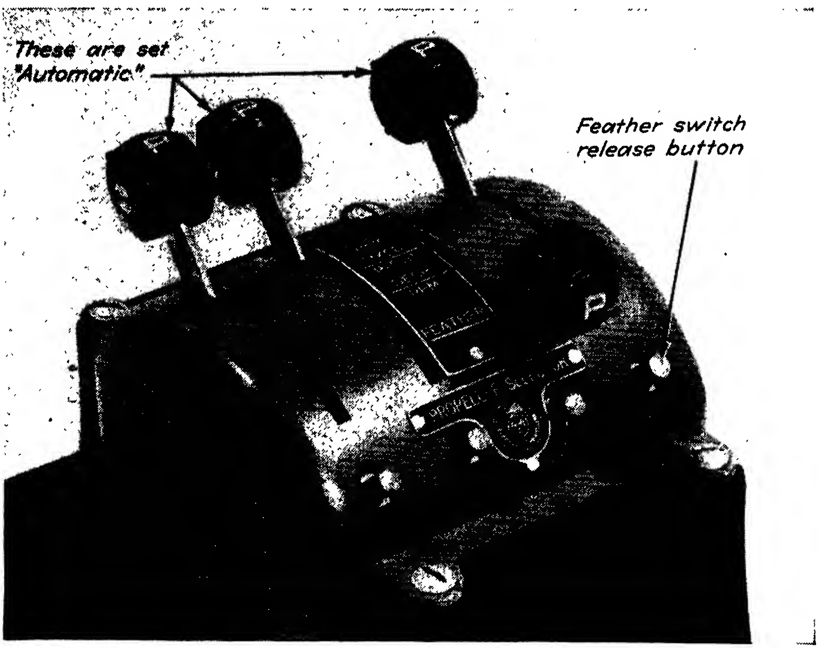


Fig. 150. Propeller operation selector. (*Curtiss Propeller Division.*)

the circuit is broken by the feather-angle limit switch at about 90°. Rotation of the propeller stops. To unfeather, if desired, the selector lever is moved to increase rpm, held there until, if in flight, the engine starts and idles slowly or until the low-pitch-angle limit switch operates.

Reversing necessitates complicated switch gear controlled by two groups of relays A and B (Fig. 148). Inadvertent reversing in the air is avoided by a latch preventing movement of the engine throttle back of the closed position. This latch is withdrawn by a solenoid activated by the closing of a switch in the landing gear when the wheels strike the ground. After the latch is out, the throttle lever can be pulled back,

closing the reverse switches that activate relays *A* and *B*. Switches in these relays close the booster circuit to the reverse brush, starting the booster, quickly reversing the propeller blades until reverse-angle limit switch opens (at −20 to −25°). Pulling engine throttle back farther opens throttle, increases rpm and engine power, hence produces the desired backward thrust. Unreversing is accomplished by pushing the throttle to "idle," which opens the throttle switches. Relay *A*

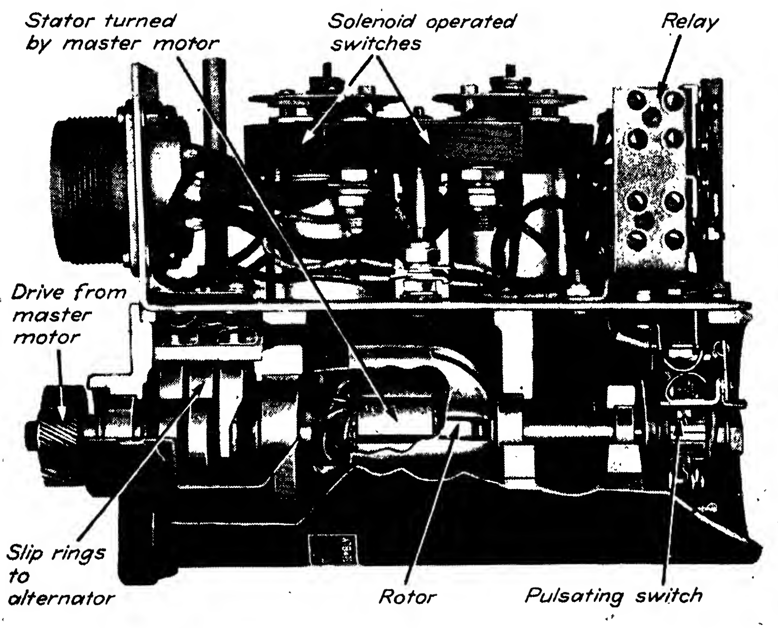


FIG. 151. Contactor. (*Curtiss Propeller Division.*)

opens; *B* does not, as it is held shut magnetically. This combination connects the booster circuit to the automatic-decrease-rpm brush, rapidly unreversing and increasing the blade angle until the auxiliary relay is tripped by the closing of the low-angle limit switches; this relay opens *B*, thus restoring normal positive-thrust operation. Since booster power is used, these actions are rapid.

Automatic control is obtained by a contactor (Fig. 151), which compares the rpm of the engine with that of one master control motor, then closes switches to adjust blade angles until the propeller lets the engine turn at the same rpm as the master motor. The rpm held constant by the master motor is adjusted by the pilot through the rpm-control

quadrant, which moves a "fixed" contact in the master motor, at from about 25 per cent less than rated rpm to the maximum allowed for take-off. The master motor (Fig. 152) is a d-c *amplidyne* motor with a portion of its control field shorted at designated rpm by a centrifugally operated contact. Closing the contacts slows the motor rapidly, thus reopening the contacts, speeding up the motor, closing the contact again. This cycle repeats about 400 times per second, and holds master-motor rpm very close to desired value. If this pulsation ceases, the control automatically returns to "manual" and blows a warning horn.

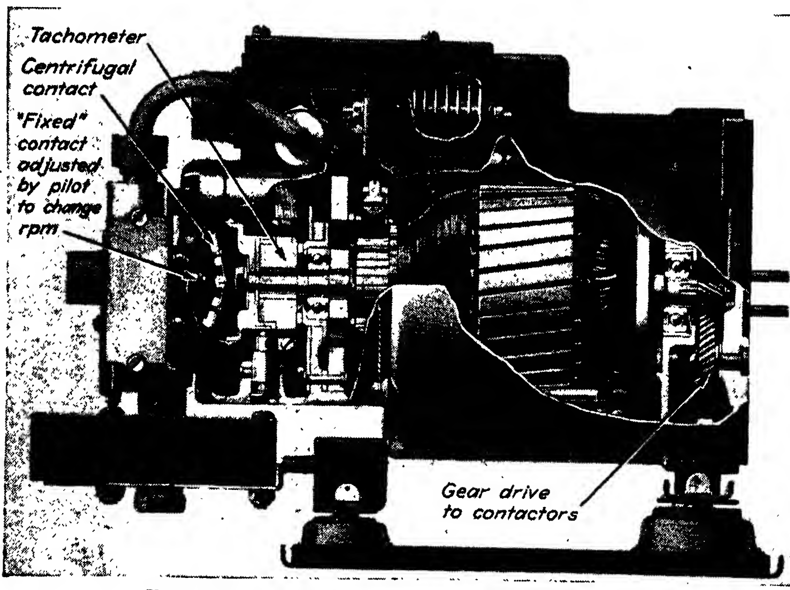


FIG. 152. Master motor. (*Curtiss Propeller Division.*)

Master motor drives mechanically a magnetic tachometer reading engine rpm and as many contactors as there are engines. On each contactor shaft is a three-phase stator winding. This winding is excited by a three-phase magneto alternator driven by the engine, giving a magnetic field that rotates *relative to the shaft* at a speed determined by the engine and in opposite direction to shaft rotation. Around the stator is a rotor cup, which will follow the rotating field. Now, if the alternator is driven by the engine at exactly the same speed that the contactor shaft is driven by the master motor, the magnetic field is fixed relative to the contactor case, and the rotor cup does not turn. If engine speed is above or below that demanded by the contactor shaft,

there will be a resultant rotation of the field, carrying along the rotor. Rotation of the rotor closes solenoid switches, intermittently sending a pulsating current to decrease engine rpm when it is too high by making the blade angle greater, or to increase engine rpm when it is too low by reducing blade angles. The engines may be thought of as *slaves* to the master motor, in that each follows closely the rpm of the master, hence the engines are synchronized with each other.

Also shown on the wiring diagram (Fig. 148) are filters required to prevent radio interference when switches operate. On the propeller hub are brushes 1 and 2; through these, current is supplied from the plane's electrical system to de-icer boots as shown on the leading edge of the blade.

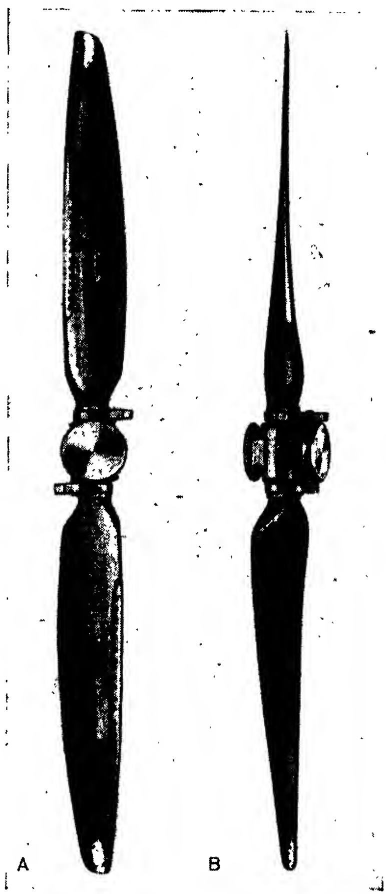


FIG. 153. "Skyblade" propeller. (*Sensenich Brothers.*)

Sensenich Controllable Propeller. For use in conjunction with smaller engines in light or small airplanes, several less complicated types of controllable-angle propellers have been manufactured. One of these is the Sensenich Skyblade propeller (Fig. 153). This propeller has two wooden blades fitted into steel ferrules. Pitch is changed by a hydraulic cylinder. The source of the hydraulic pressure is the engine oil system. The front end of the crankshaft must be hollow and blocked off from the rest of the shaft. A radial hole in the shaft leads to a hollow ring in the crankcase, thence to a three-way valve. This two-position valve, actuated by the pilot, allows engine oil to flow into the propeller under pressure or to escape from the propeller to crankcase. These special fittings must be built into the engine.

The hub, shown cutaway on Fig. 154, is supported on the engine

shaft and bolted to the shaft flange 1. The wooden blades are pressed into steel ferrules 2 and held by many long lag screws. Blades are held in hub by a split retaining ring 3, a roller thrust bearing 4, and retaining nut 5. Blade angle is adjusted through a lug 6 in a plate screwed to the inner face of the ferrule. The pitch-change lever 7 fits over the lug (on the cutaway figure only half the lever is shown), pivots on a pin in the hub, and its opposite end is pinned to the hydraulic cylinder 8

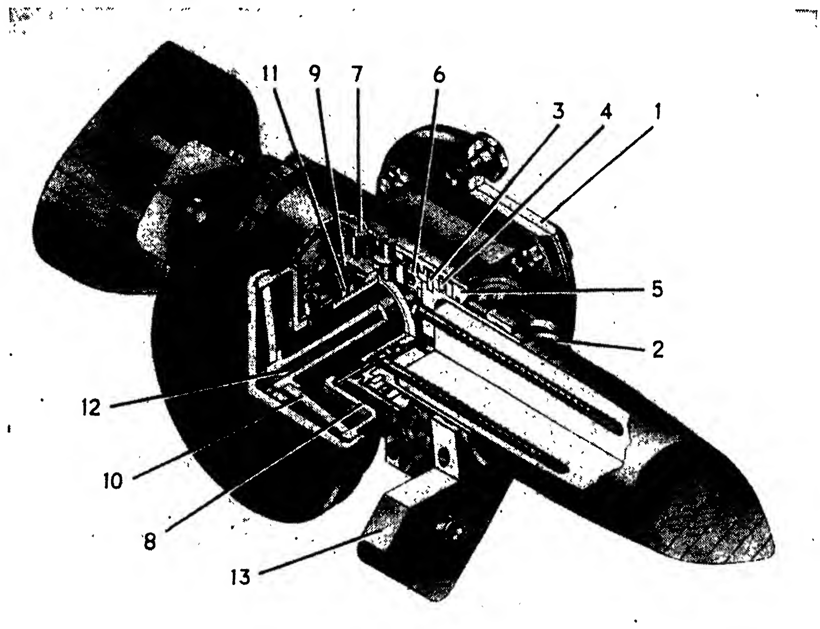


Fig. 154. Hub of "Skyblade" propeller. (*Sensenich Brothers.*)

through an axially adjustable nut 9. The cylinder fits over a fixed plastic piston 10 with neoprene (synthetic-rubber) seal and slides in plastic bushings in the hub. Axial motion is limited forward by an adjustable "low-pitch" nut 11 on the outside of the cylinder, backward by the piston itself. Angle of pitch change from high (piston back) to low (piston forward) depends on the low-pitch adjustment. Small changes in high-pitch angle are made by turning the cylinder so that nut 9 moves axially (forward reduces the high-pitch setting). Large changes are made by indexing blade on ferrule plate. An oil tube 12 connects the space inside the cylinder to the hollow engine shaft and oil valve.

In operation, when the three-way control valve is open to the crank-

case, the effect of centrifugal twisting moment on the blades and counterweights 13 is to force the blades into high-pitch (low-rpm) position, pushing oil in the cylinder out into the crankcase. If the three-way valve is turned to connect the engine oil system to the cylinder, oil pressure is sufficient to force the blades back into the low-pitch (high-rpm) position. The system is similar in principle to that used much earlier in the Hamilton Standard two-position propellers.

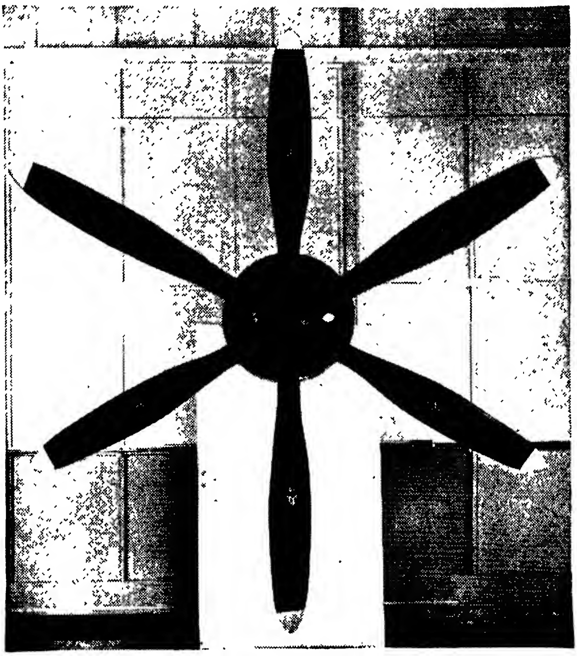


Fig. 155. Dual-rotation propeller. (*Curtiss Propeller Division.*)

Dual-rotation Propellers. To avoid difficulties in airplane control arising from the rotation of the propeller slipstream, which become particularly serious on high-powered airplanes with single engines, the propeller may be divided into two sections rotating in opposite directions; hence this type is called a dual-rotation or *counterrotating* propeller (Fig. 155). The front blades twist the slipstream, but the rear blades twist it back, thus the result is a slipstream almost without twist. Since the twist is a loss, dual-rotation propellers are very slightly more efficient than the simpler single-rotating ones. Such a propeller requires a special gearbox on the engine or must provide it in the hub. Controllable-angle mechanism is also complicated.

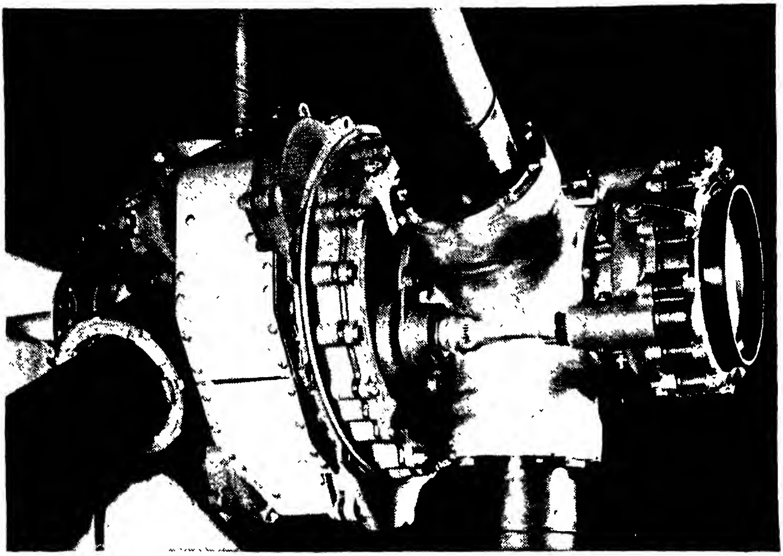


FIG. 156. Hub of dual-rotation propeller. (*Curtiss Propeller Division.*)

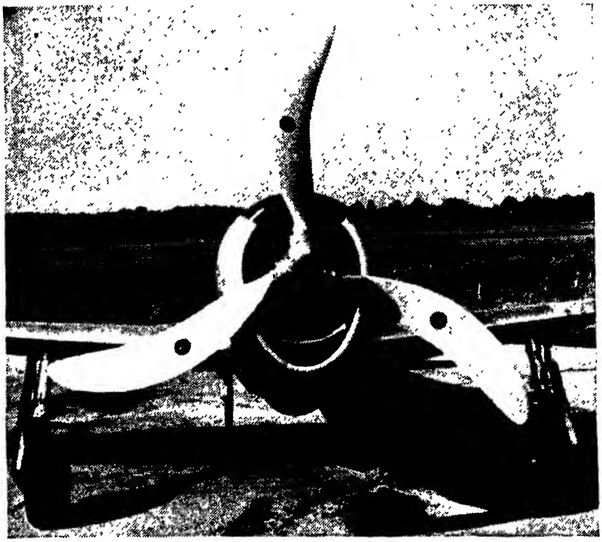


FIG. 157. Propeller with sweptback blade. (*Curtiss Propeller Division.*)

(Fig. 156). These difficulties increase the weight of dual-rotation propellers.

Another idea, which has some advantage in postponing to higher Mach number the loss of efficiency due to Mach number, is to arrange the leading edge of the propeller to meet the air slantwise instead of straight on. This corresponds to a wing with sweepback. Such a propeller (Fig. 157) has a few per cent better efficiency at high tip speeds than a straight one that is otherwise similar.

CHAPTER XI

AIRPLANE PERFORMANCE

The value of an airplane depends on how well it can fly in the air with the load that it is intended to carry, and the object of every designer is to produce an airplane whose accomplishments are the utmost that can be attained with the means at his disposal. It is difficult to define and evaluate how well the airplane can fly. Flying qualities and maneuverability are so intangible that opinions of pilots must often be used in place of measurements. Some tests of stability and controllability are possible, but here also much depends on pilots' opinions. Other characteristics, such as speed, may readily be given numerical values and are grouped under the general term *performance.* Different items that are included in performance and the units in which they are usually expressed follow:

Maximum speed at sea level and various altitudes, in miles per hour.

Landing speed at sea level, in miles per hour.

Maximum rate of climb at sea level and various altitudes, in miles per hour.

Maximum angle of climb at sea level, in degrees.

Time required to reach various altitudes, in minutes.

Ceiling or the maximum attainable altitude, in feet.

Range, the maximum distance that the airplane can cover without refueling, in miles. Alternatively fuel consumption in gallons per mile or per hour may be determined.

Take-off distance, in feet.

All these characteristics are dependent on the total weight of the airplane. Therefore every report on the performance of an airplane must state the weight for which the performance is given. If the weight is not given, it is understood that the plane is carrying its normal load, which is usually well known.

The performance of an airplane depends primarily on two quantities: the *power required* or *drag horsepower* and the *power available* or *thrust horsepower. Drag horsepower* is that needed to push the airplane through the air. *Thrust horsepower* is that given by the power plant to the airplane under specified conditions. Both powers vary with speed and altitude. Thrust horsepower is equal to drag horsepower only when the airplane is flying along a straight level path at constant air

speed. A more detailed consideration of these two quantities will show how the relation between them determines the performance of the airplane.

Equilibrium of Forces. In steady flight on a straight path, the forces on the plane must be in equilibrium. Several conditions are shown on Fig. 158. Lift may be considered equal to weight for small slopes of flight path.

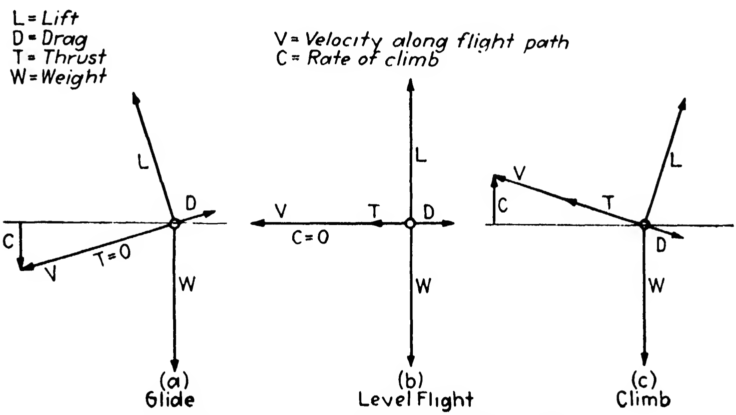


FIG. 158. Forces on airplane in steady flight.

a. The flight path is inclined downward; slope is $(D - T)/W$ or C/V.
b. The flight path is level, $D = T$.
c. The flight path is inclined upward; slope is $(T - D)/W$ or C/V.
The rate of climb, C, may be found from the last relation,

$$\frac{C}{V} = \frac{T - D}{W} \tag{1}$$

$$C = \frac{TV - DV}{W} \tag{2}$$

T is the thrust from the propeller or jet and, if the throttle is wide open, is the maximum thrust.

The product TV is the power; if this is divided by 550, the thrust horsepower or horsepower available from the power plant, thp, is obtained.

The product DV is the power needed to push the airplane through the air; dividing by 550 gives the horsepower required or drag horsepower, dhp.

The equation may be written

$$C = \frac{(\text{thp} - \text{dhp})33{,}000}{W} \tag{3}$$

giving C in feet per minute.

By itself (thp/W)33,000 is the rate at which the airplane would ascend if it had no drag; (dhp/W)33,000 is the rate at which the airplane would descend if there were no thrust. The latter is called the *sinking speed.* To make it small, both D and V must be small.

Power Required. For a given airplane, the drag horsepower is found by evaluating the drag at various values of the speed. The drag, as previously explained in Chaps. III and IV, may be considered as made up of induced drag D_i, resulting from the lift, and the remainder, D_P, the parasite drag.

$$D_i = \frac{L^2}{\pi q b^2} \tag{4}$$

where L = lift
q = dynamic pressure
b = span

$$D_P = C_{DP} S q \tag{5}$$

where S = wing area
C_{DP} = parasite drag coefficient

If C_{DP} is regarded as a constant at all speeds, a factor e should be included with the induced drag to allow approximately for the actual variation of C_{DP}. e varies from 0.70 to 1.00.

Recall that

$q = 0.0334dV^2$ V in mph
L = weight d = air density, lb per cu ft

$$D = \frac{W^2}{\pi q e b^2} + C_{DP} S q \tag{6}$$

C_{DP} can be found by summing the drags of the parts; or the total may be estimated.

$$\text{dhp} = \frac{88DV}{550 \times 60} \qquad V \text{ in mph}$$

$$= \frac{DV}{375} \tag{7}$$

Alternately, the drag of the airplane or of an exact model may be found in a *wind tunnel.* If the model is small, minor parts cannot be reproduced and the flow pattern will not be quite similar to that around the airplane. *Scale-effect* corrections are made by the engineer to allow

for such discrepancies, but since they are of uncertain magnitude, it is very desirable that the size and speed of test be as large as possible. A wind tunnel is merely a device for creating an air stream of uniform velocity. The NACA has several large wind tunnels; a model, in this case the airplane itself, is shown mounted for test in the largest wind tunnel in Fig. 159.

The model is supported on a *balance;* lift and drag forces are measured for angles of attack from zero lift to beyond the stall. The pro-

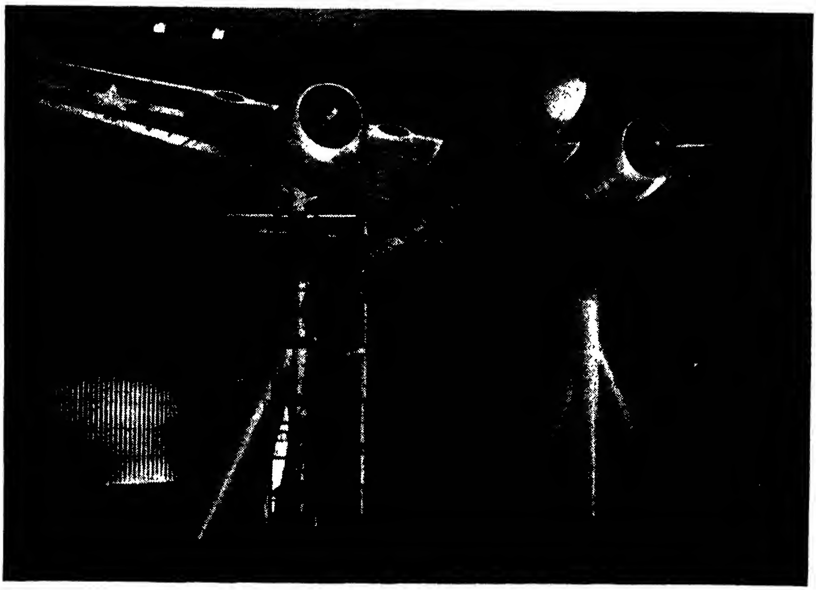


FIG. 159. Airplane in wind tunnel. (*National Advisory Committee for Aeronautics.*)

cedure is the same as illustrated for airfoils in Chap. II. Coefficients of lift and total airplane drag are calculated.

From these data or by direct calculation, the drag horsepower may be found and plotted against V, as shown at A on Fig. 160, for sea level. If the approximate method of allowing for the variation of C_{DP} with V (or angle of attack) were used, the drag-horsepower curve would not have the hook at the lower end. This double value of drag horsepower at speeds above minimum V results from the double value of drag coefficient at lift coefficients just below maximum, the lower at angles of attack less than the stall, the higher with wing stalled. The airplane is never flown beyond the stall, nor close to it in steady flight. Hence the extreme left portion of the drag-horsepower curve is of little impor-

tance. Except in this region, the algebraic approximation for the variation of drag with velocity agrees well with the experimental curve. From the wind-tunnel tests, e and the now-constant value C_{DP} may be found. The particular curves on the figure are drawn for an imaginary twin-engine transport having the following characteristics: weight, 35,000 lb; wing area, 900 sq ft; span, 85 ft; C_{DP}, 0.025.

Variation of drag horsepower with air speed and altitude are clearly shown by the approximate method.

$$\begin{aligned}\text{dhp} &= \frac{DV}{375} = \frac{V}{375}\left(\frac{W^2}{\pi e b^2 q} + C_{DP}Sq\right) \\ &= \frac{W^2}{375\pi e b^2 \times 0.0334 dV} + \frac{C_{DP}S \times 0.0334 dV^3}{375} \\ &= \frac{K_1}{dV} + K_2 dV^3 \qquad (8)\end{aligned}$$

At constant altitude, *i.e.*, constant density of air, power at high speed varies nearly as V^3, since when V is large the first term becomes small. A reservation to this rule must be made, since if V is so high that Mach number is greater than 0.6 or thereabouts, C_{DP}, hence K_2, cannot be considered constant but increases with V, and the drag horsepower will vary much faster than V^3. With change in altitude at constant V, the induced part of drag horsepower varies inversely with density, while the parasite part varies directly with density; therefore at low speeds more power is needed at altitude, but at most speeds much less power is required at altitude, as shown also on Fig. 160. Minimum power increases as $1/\sqrt{d}$, but minimum total drag is independent of altitude. (Curves are for same airplane with same weight; maximum L/D is same, depending only on shape, not on altitude; minimum drag is weight/maximum L/D, hence is independent of altitude.) Minimum drag occurs at the speeds where the tangent from the origin meets the curves; this changes from 145 mph at 0 ft altitude to 213 mph at 24,000 ft altitude.

Thrust Horsepower. The magnitude and even the character of curves showing the variation of thrust horsepower with air speed depend on the type and size of power plant. First a conventional reciprocating-engine–propeller power plant will be considered. For the sample airplane, two engines rated at 1,800 bhp each from sea level to critical altitude of 8,000 ft would be reasonable. Each engine turns a three-blade propeller, 12 ft 8 in. in diameter, at 1,400 rated rpm. For such a plane controllable-angle propellers would be used. At rated power and rpm, propeller efficiency E can be found from curves similar

to those of Figs. 125 and 126, since power coefficient C_P and V/nD can be calculated from already-known brake horsepower, rpm, diameter, air density, and velocity. C_P and V/nD fix blade angle and E. Then

$$\text{thp} = \text{bhp} \times E$$

In Fig. 160 at B, the thrust horsepower for 0 and 8,000 ft are plotted. At altitudes above the critical, the maximum brake horsepower will

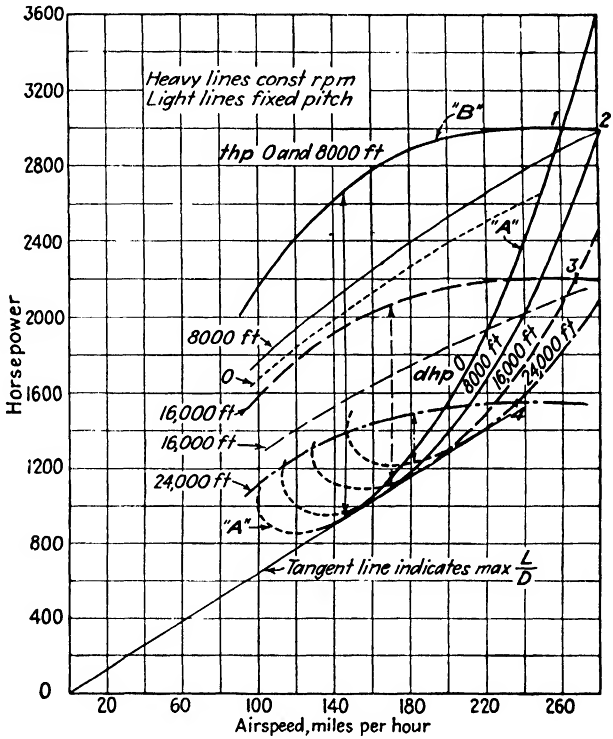


FIG. 160. Curves of drag and thrust horsepowers.

decrease slightly faster than the density decreases; propeller efficiency will be hardly changed. Curves of thrust horsepower for higher altitudes are included in Fig. 160.

Maximum Performance. Before discussing effects of power-plant changes, performance shown by these curves will be found. For each pair of thrust-horsepower and drag-horsepower curves, maximum speed in level flight with full power is given by the intersection of these curves where thrust horsepower equals drag horsepower. From points 1, 2, 3,

4, in Fig. 160, maximum speeds are read as 262 mph at sea level, 281 at 8,000 ft, 267 at 16,000 ft, and 236 at 24,000 ft.

Rate of climb at any air speed is found from excess of thrust horsepower over drag horsepower at that speed. At sea level at 146 mph, thp − dhp = 1,720, and rate of climb $C = 1{,}720 \dfrac{33{,}000}{35{,}000} = 1{,}620$ ft per min. By trial, maximum rates of climb with full power are 1,620 ft

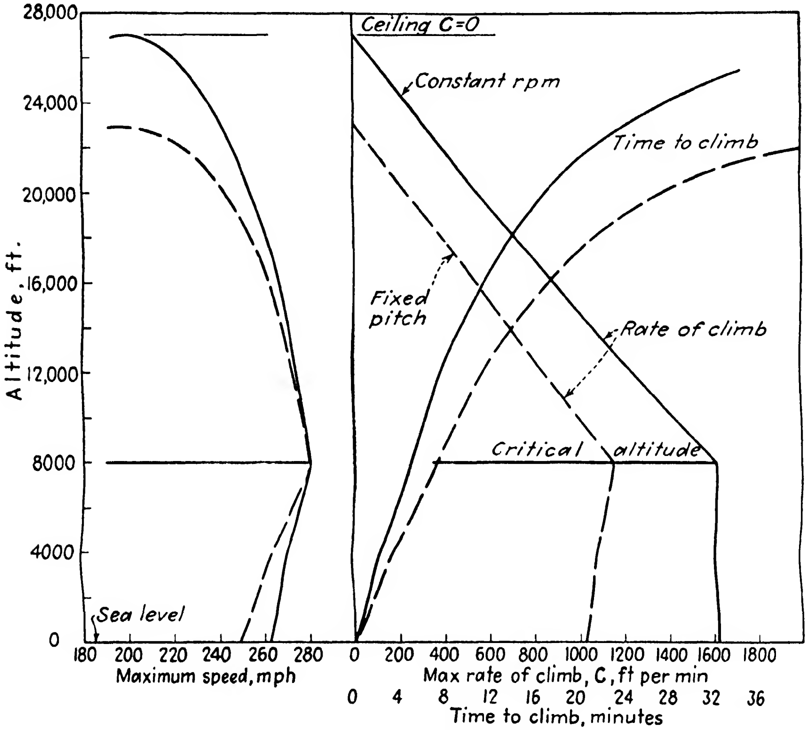


FIG. 161. Performance curves.

per min at sea level or 8,000 ft, 890 at 16,000 ft, 240 at 24,000 ft. The ceiling, the altitude where best rate of climb is 0, would be about 27,000 ft (see Fig. 161). The angle of climb is found by dividing the rate of climb by the air speed; *e.g.*, at 130 mph at sea level

$$\text{Angle of climb} = \frac{57 \times \text{rate of climb}}{88 \times \text{air speed}} = \frac{57 \times 1{,}560}{88 \times 130} = 7.8^\circ$$

At this air speed the angle is nearly its maximum at sea level. For take-off, more than rated power is usually permitted; hence angle for

climbing off an airport will be larger (about 25 per cent) but still not high. At higher altitudes, angle of climb will be less.

In some cases, time to reach an altitude is important. This may be found from the rate of climb. If the rate for any interval of height is constant then time

$$t = \frac{\text{height interval}}{\text{rate}}$$

If the rate of climb varies, the average is used to find the time for a short interval; then these times are added to find the total time. The average for a large interval of height cannot be used, since too short a time would result. In Fig. 161, with controllable propeller, for 0 to 8,000 ft, C is 1,620 ft per min; hence time is 8,000/1,620 or 4.9 min; other times are included in Table 11. Smaller intervals in Table 11

TABLE 11

Height, ft	Interval, ft	Average rate, ft/min	Time for interval, min	Total time, min
8,000	8,000	1,620	4.9	4.9
12,000	4,000	1,430	2.8	7.7
16,000	4,000	1,070	3.7	11.4
20,000	4,000	720	5.6	17.0
23,000	3,000	440	6.8	23.8
25,000	2,000	240	8.3	32.1

would give a slightly larger and more exact time. If the average rate, 890 ft per min from 8,000 to 25,000 ft were used, for that 17,000-ft interval the time found would be 8 min too short. The time to reach 20,000 ft is 17 min; in that time the plane will travel about 45 miles.

Cruising Speed. Cruising speed is a poorly defined level speed low enough so that engine wear and maintenance costs are minimized, high enough to make the plane attractive to the user. For short or moderate distances about seven-eighths of the speed with maximum power is often used. Since this is still fairly "high," thrust and brake horsepower will both vary nearly as V^3 so that $\frac{7}{8}V_{max}$ will require about 70 per cent power. At sea level for the sample airplane, 70 per cent rated power gives a cruising speed of 228 mph, but a gain can be made without exceeding that brake horsepower by cruising at altitude. For example, at 16,000 ft and 70 per cent rated power, the speed is 262 mph (the same reached at full power at sea level) or a gain of 15 per cent practically free; therefore air-line flight plans for moderate distances

always use high altitudes unless winds are adverse. For the sample airplane, the cruising altitude at 70 per cent power could not be higher than 16,000 ft, since at that altitude the engine is operating at almost wide-open throttle. For extremely long range, much slower speed is optimum, as explained in the footnote (page 226) under comparison of performance with reciprocating and turbojet engines.

Take-off. In order to reach safe flying speed, the airplane must be accelerated from a standstill along a smooth runway until a speed 10 or 15 per cent higher than stalling is reached; then the airplane takes off. Take-off for many airplanes is made with flaps partly down to reduce the stalling speed. The distance can be estimated closely if the acceleration found at 70 per cent of take-off speed is assumed uniform throughout the run. The fundamental relations of physics are

$$\text{Acceleration } a = \frac{\text{force}}{wt} \times 32.2$$

$$\text{Distance } S = \frac{V_{t\text{-}o}^2}{2a}$$

$V_{t\text{-}o}$ must be in feet per second.

$$\text{Force } F = \text{thrust} - (\text{drag} + \text{ground resistance})$$

At 70 per cent take-off speed, the weight of the plane is about evenly divided between the wings and the wheels. L/D may be about 10, ground resistance about 5 per cent of load on wheels. For the sample plane, take-off horsepower would be 4,000 (about 10 per cent higher than rated), efficiency about 50 per cent, take-off velocity 150 ft per sec.

$$T = \frac{\text{bhp} \times E}{v} \times 550 = 10{,}000 \text{ lb for the sample plane}$$

$$F = 10{,}000 - 2{,}600 = 7{,}400 \text{ lb}$$

$$a = \frac{7{,}400}{35{,}000} \times 32.2 = 6.8 \text{ ft per sec per sec}$$

$$S = \frac{150^2}{2 \times 6.8} = 1{,}700 \text{ ft}$$

To clear an obstacle, say 50 ft high, an additional 400 ft would be needed, or a total of 2,100 ft. If take-off is made against a wind of 10 per cent of take-off velocity, the take-off distance would be reduced by about 20 per cent.

Effect of Changes. To illustrate the effect on performance of changes other than variation of altitude, some arbitrary modifications of power plant will be made. Simplest is to replace the controllable-

pitch constant-rpm propeller with one with fixed pitch. The principal effect is that the engine will not turn the propeller at full rated rpm except under one condition. The thrust horsepower of the fixed-pitch propeller is also shown in Fig. 160. The reduction in speed and rate of climb with full power are shown in Fig. 161 compared with those obtained for the constant-rpm propeller. The fixed-pitch propeller was selected to give the same maximum speed at critical altitude as the constant-rpm propeller. Rate of climb is materially reduced at all altitudes. Ceiling is lowered.

Effect of radical changes in the airplane are shown in Fig. 162 for 8,000 ft altitude. Horsepower required, A, is for the original plane reproduced from Fig. 160. For curve B the parasite drag is halved; such a reduction would be impossible to achieve unless a change to a flying wing is imagined. With the original power plant but revised propeller, the thrust-horsepower dash-dot curve shows maximum speed is increased from 281 to 360 mph, maximum rate of climb from 1,620 to 1,870 ft per min. The maximum L/D is increased from 14.5 at 160 mph to 19.9 at 200; not only is the L/D increased by over one-third, but the higher air speed is also desirable.

For curve C in Fig. 162, the induced drag has been doubled; this would result from reducing the span until $(\text{span})^2$ is half the original, or from 85 to 60 ft with weight remaining at 35,000 lb, or alternatively increasing the weight to 49,000 lb without changing the span. Hence curve C represents the drag horsepower for two different airplanes. Using the thrust horsepower from the original propellers, maximum speed for either plane is reduced, but only a little, to 260 mph. Maximum rate of climb for the short-span plane is only 1,140 instead of 1,620 for the original span. Effect of the large weight increase is to reduce rate of climb even lower, to 810 ft per min (that this is half the original 1,620 is accidental). Therefore, the effect of the weight increase on rate of climb is much greater than on maximum speed; the penalty is double: less excess horsepower and simultaneously more weight for it to lift. The minimum drag force for both planes represented by C is the same, 3,420 lb, but maximum L/D for the long-span overloaded plane is 14.5, while that for the short-span plane is only 10.4.

For the original plane, two conventional reciprocating engines rated at 1,800 bhp each for altitudes up to 8,000 ft were used. Such engines would have single-speed single-stage centrifugal superchargers, gear-driven by the engine crankshaft. Below critical altitude of 8,000 ft, throttle must be partly closed, limiting power to the 1,800 bhp of each

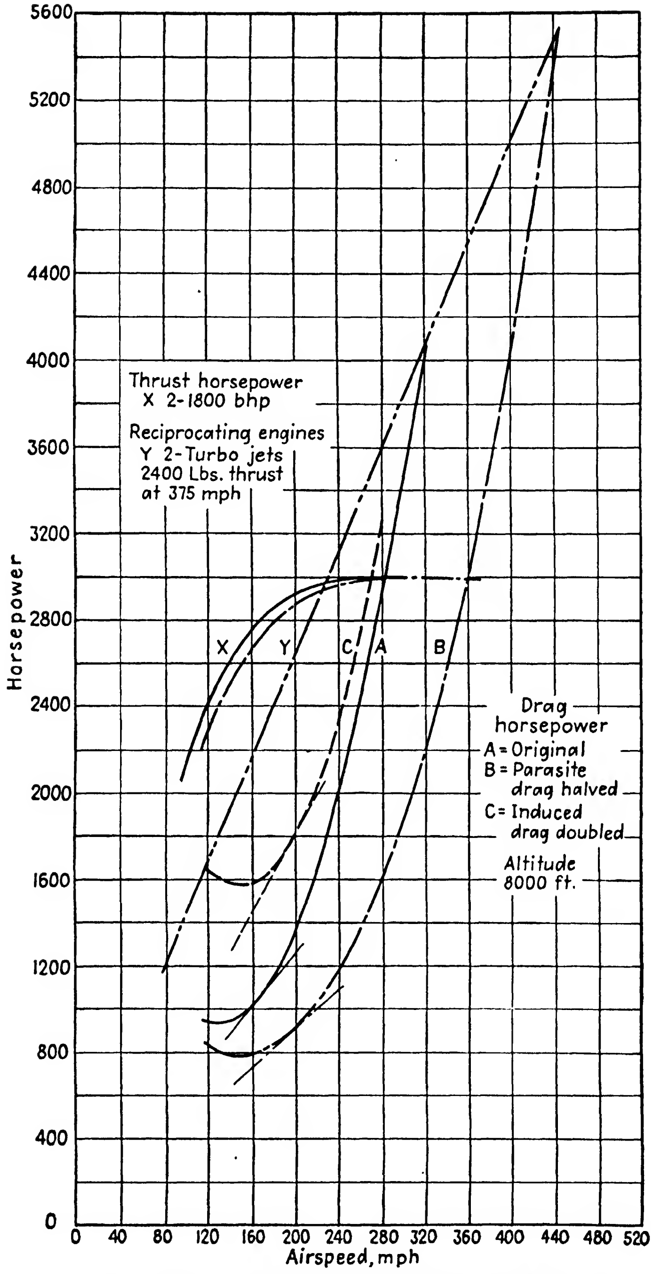


FIG. 162. Effect of changes on drag and thrust horsepowers.

engine, to prevent damage to the engine through excessive detonation stresses (Chap. IX). If the engines should be fitted with exhaust-turbine-driven superchargers in addition to the geared ones, the rated power could be maintained to much higher altitude, *e.g.*, to 24,000 ft, without much trouble. By proper selection of the propeller, maximum thrust horsepower at 24,000 ft could be maintained at the 3,000 (for both engines) shown in Fig. 163 for the conventional engines at 8,000 ft altitude. Turbosupercharged engines would increase the maximum speed at 24,000 ft from 236 to about 360 mph, which is 80 mph faster than maximum speed at critical altitude without the turbosuperchargers. If the effectiveness of the exhaust turbosupercharger system and propeller could be maintained to much higher altitudes, so that 3,000 thp was available, the highest maximum speed would be obtained when the plane flies in level flight at maximum L/D at full power. For the sample, the speed would be a little over 450 mph at about 50,000 ft altitude, not within practical reach.

A radical change in power plant would be to replace the reciprocating engines and propellers with two turbojet engines. The performance characteristics of such engines are that the full thrust varies, but only slowly, with forward speed; that the thrust at fixed speed varies almost directly with the air density; that the critical altitude is sea level. Choice of size was made to make maximum rate of climb with turbojets in the low-parasite-drag airplane, B in Fig. 162 (it would be a waste even to consider jets in the normal-drag plane) the same as that with the propellers. This rate of climb needed two turbojets giving 2,400 lb of thrust each at 375 mph at 8,000 ft. Rating would be about 3,400 lb static thrust each at sea level. The jets would give thrust horsepower shown by Y in Fig. 162. Maximum level speed is increased from 360 mph with the propeller airplane to 440 mph for the turbojet airplane. Maximum rate of climb is 1,870 ft per min for each, but for the jet plane this occurs at about 280 mph instead of at 180 for the propeller plane. Below 200 mph the propeller plane has better climb than the jet plane.

Some other comparisons of the performance with the two power plants may be made. The total power-plant weight for the reciprocating-engine–propeller plane would be about 7,600 lb (2.1 lb per rated brake horsepower). The probable weight for the turbojet power plant would be 4,000 lb (0.6 lb per pound of static thrust). This saving can be added to the pay load or fuel load. At 8,000 ft altitude, the maximum miles per gallon of gasoline can be estimated. For the propeller plane, this would be about 2.0 at 200 mph. For the jet plane, maximum miles per gallon of fuel would be about 0.9 at 270 mph. The weight

saving is absorbed by added fuel burned in about 700 miles. At higher altitudes, say 24,000 ft, the jet mileage would increase to about 1.2, while the mileage for the propeller plane is generally independent of the altitude.[1] For the original high-drag airplane, the best miles per gallon would be about 1.5 (superior to that of the jet low-drag plane at 24,000 ft altitude). The size of the jets was determined to give equal rates of climb at 8,000 ft altitude. Maximum thrust at sea level for both jets of this size with 10 per cent increase for take-off is about 7,500 lb. This is less than the 10,000 lb estimated for the propeller-driven plane. The lower thrust adds just about 50 per cent to the take-off distance estimated for the example using propellers. Of course, selection of larger jets would improve take-off, and also high speed and rate of climb, but would entail heavier power-plant weight and occupy more space. Summarizing for moderately powered planes such as the low-drag example, the turbojet engine effects a substantial saving in power-plant weight, increases the speeds, but sacrifices fuel economy and take-off.

More generally the weight savings become more and more important

[1] Methods of estimating the mileage are approximate. For propeller-driven airplanes, lowest consumption of fuel per mile in still air is at a speed just above that for maximum L/D.

$$\frac{\text{bhp} \times \text{sfc}}{V} = \frac{\text{lb per hr}}{V} = \text{lb per mile}$$

$$\frac{\text{drag} \times V \times \text{sfc}}{EV \times 375} = \text{lb per mile}$$

$$\frac{\text{weight}}{(L/D)_{\max}} \frac{\text{sfc}}{\times 375\ E} = \text{lb per mile}$$

Gasoline weighs 6 lb per gal; therefore

$$\text{Miles per gal} = \frac{6}{\text{lb per mile}}$$

sfc was used as 0.5 lb per bhp per hr, E, propeller efficiency, as 80 per cent.

For the jet planes, lowest consumption per mile is at a speed one-third higher than that for maximum L/D.

$$\frac{\text{thrust} \times \text{fc}}{V} = \frac{\text{lb per hr}}{V} = \text{lb per mile}$$

$$\frac{\text{thp} \times 375 \times \text{fc}}{V \times V} = \text{lb per mile}$$

Jet fuel may weigh 7 lb per gal; therefore

$$\text{Miles per gal} = \frac{7}{\text{lb per mile}}$$

Fuel consumption was taken as 1.0 lb per hr per lb of thrust.

as flight speed is increased, until for airplanes in the 600-mph class, that advantage for the jet outweighs all other considerations. In addition, at such high flight speeds, propeller efficiencies are reduced by the high Mach number, while jet efficiencies are improved; this results in loss of the economy advantage for the reciprocating-engine–propeller airplanes.

Another different power plant that might be used in the sample airplane is a turbine driving a propeller or a *turboprop*. If the engines were selected to give the same brake horsepower (including effect of exhaust jet) at 8,000 ft, thrust horsepower would be very nearly the same as that from the reciprocating engine. The weight of the power plant would be approximately halved, while fuel consumption would probably be 10 or 15 per cent greater than for the reciprocating engine. Airplane drag could be slightly reduced.

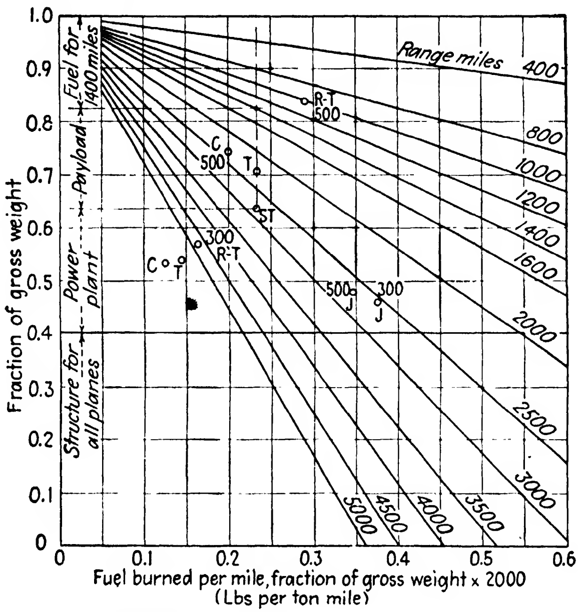
In general, the principal advantage of the turboprop engine to the airplane performance results from the weight saving. This is sufficient at low altitudes (up to about 25,000 ft) to permit the extension of the speed of propeller-driven airplanes beyond the limit set by the power-plant weight if reciprocating engines are used. At higher altitudes, skillful design and utilization of supercharging permits building of reciprocating engines with high critical altitude that weigh less than the present (1948) turbines for the high altitude, principally because superchargers cannot be used on the turbines.

In this chapter, merits of different types of power plant are considered only from changes in the performance of the airplane, without reference to cost, maintenance problems, reliability, or safety.

For level flight at a given speed, altitude, and range, that type of power plant is best which, together with necessary fuel for the trip, weighs least, since with it a larger per cent of the gross weight of the airplane can be pay load. If the speed or altitude are high, power will be sufficient for take-off and climb safety. At subsonic speeds with reasonable ranges, there are three competing types: reciprocating engines with propellers, turboprop engines, and turbojet engines. Ramjets and rocket engines do not have satisfactory fuel consumption. There may be several modifications of the reciprocating engine: the usual type with a gear-driven supercharger, the high-altitude type with exhaust-turbodriven supercharger, and one, the compound engine, that resembles the turbosupercharged except that the exhaust-driven turbine helps to turn the propeller through gears.

By use of plots like Fig. 163, comparison can be made for different power plants. On the plot the abscissa is pounds of fuel per mile

divided by weight of plane in tons; the ordinate shows the fraction of total weight needed for the structure (40 per cent), for the power plant (variable percentage), for fuel, tanks, and pay load (the rest). For the ideal plane at any speed and altitude, the best possible power plants of several types are selected, and abscissa and ordinate are calculated.



Spots are for a particular airplane:
S-T—Sample transport, 200 mph at 20,000 ft
C—Compound engine, 300 and 500 mph at 30,000 ft
T—Turboprop engine, 300 and 500 mph at 30,000 ft
R-T—Reciprocating engine turbosupercharger, 300 and 500 mph at 30,000 ft
J—Turbojet engine, 300 and 500 mph at 30,000 ft

FIG. 163. Range of ideal planes. (*Data from NACA.*)

Lines of constant range can be drawn since

$$\text{Range} = \frac{\text{fraction of weight for fuel and tank} \times 2{,}000}{\text{fuel per ton-mile} \times 1.10}$$

The extra 1.10 is for tanks. L/D of plane without engine nacelles is 18 unless W/S exceeds 80 lb per sq ft. Points for eight ideal planes are shown, while the point for the sample transport of our example is included to show how an ordinary plane compares with these ideal ones.

From these analyses some general conclusions can be made. At 30,000 ft at 300 mph, the compound engine gives best range followed closely by the turboprop and turbosupercharged, with turbojet far behind; but at 500 mph turbojet has slightly the best range. Power-

plant weight for turbojets is extremely small, not only because the engine specific weight is low but also because the drag for nacelles and cooling is much smaller than for the reciprocating engines. Such a low power-plant weight means large pay loads for short range; *e.g.*, at 30,000 ft and 300 mph, maximum range for reciprocating engine with turbosupercharger is 4,900 miles, for turbojet 2,600 miles, but up to 800-mile trips, the turbojet plane will carry more pay load. The reciprocating engine weighed too much to give its ideal plane a speed of 500 mph at sea level, though at 30,000 ft, 500 mph was attained by both compound and turbosupercharged engines, since airplane drag is much less.

The sample transport will carry pay load up to 18 per cent gross weight for a range of 1,400 miles at about 200 mph at 20,000 ft, while the ideal planes would have same range and pay load at 30,000 ft at speeds of about

Turbosupercharged reciprocating	420 mph
Turboprop	460 mph
Turbojet	Nearly 600 mph

Similar study of supersonic aircraft with wing L/D of 7 indicates the possibility of flight at 1,400 mph with turbojet power plant weighing only 10 per cent of total weight. Fuel rate at 30,000 ft is 1.15 lb per ton-mile; for similar power plant at 500 mph, it is only 0.33 per ton-mile. The aircraft are fictitious but the analysis is based on well-considered data.

Performance Testing. It might be inferred from the preceding discussion of curves and other rather theoretical matters that the determination of airplane performance is chiefly a matter of calculation. This is by no means the case, and under most conditions the best means of determining performance is by testing the airplane in flight under known conditions. Performance testing, however, is not easy and not every pilot does it well. It is necessary that performance tests be made under good weather conditions, for the effects of rough air and irregular currents may be enough to cause large errors.

The easiest airplane characteristic to determine by test is maximum speed at sea level. This involves only a determination of the time necessary for the airplane to fly over a measured course laid out on the level ground. To eliminate the effect of wind, the speed is ordinarily taken as the average of that on four runs, two in each direction. Great care in timing is essential, for ordinarily the airplane speed is so high in proportion to the length of the course that even a very small error in starting or stopping the watch makes a very appreciable difference in

the apparent speed of the airplane. The practice of announcing airplane speeds in races in hundredths or thousandths of a mile per hour is absurd. A determination correct to the nearest tenth of a mile per hour is exceedingly good.

Obviously the airplane must fly level while the time is being observed, for if it flies downhill the speed is exaggerated, as is also the case if the airplane dives just as it enters the course. A cross wind reduces the apparent speed, because it carries the airplane off somewhat to the side and so requires it to fly a greater distance through the air than that which it covers over the ground. This error, however, is rather less than is commonly supposed. If, for example, the wind is blowing at right angles to the course with a speed one-tenth that of the airplane, the apparent airplane speed is only ½ of 1 per cent less than the true speed.

For determining the speed in ordinary flight, the airplane is usually provided with an air-speed indicator, such as is described in Chap. XVII. This instrument is not considered accurate enough for use in test flights until it has been calibrated, *i.e.*, until its errors have been found by comparing its indicated speeds with those calculated by timing the machine over a measured course. Since the reading of the air-speed indicator depends on the density of the air as well as on the speed of the airplane, it is necessary to make an allowance for any difference between the actual air density and the standard density at which the instrument is intended to read correctly. Even at sea level this density correction may be as much as 8 mph in a high-speed airplane, and at higher altitudes it is evidently much greater than this.

Minimum speed would be just as easily determined as maximum speed were it not for the fact that most airplanes when flying near the stalling angle are not easy to control. In order that the times for the course may be taken accurately, it is necessary for the airplane to fly at a height of not much more than 100 ft, and under these conditions there is little opportunity for recovery from a temporary loss of control. The lowest speed that the pilot considers safe may therefore be somewhat above the true minimum speed of the airplane. There are other methods for determining minimum speed, but they are indirect and require tests with special instruments. The ordinary air-speed indicator is not very reliable at low speeds. The estimate of an observer who, without instruments, watches the airplane as it comes in to land is even less reliable.

It is necessary to distinguish carefully between the minimum air

speed and the landing speed relative to the ground, which is the air speed minus the wind speed.

Rate of climb is found by keeping a record of the time required to attain different altitudes. Such a determination may not be extremely accurate, even under the best conditions, on account of instrument errors, atmospheric irregularities, and variations in engine performance. Speeds at altitudes far above the ground must ordinarily be determined from a calibrated air-speed meter, with the altimeter reading held constant to make sure that the airplane is being flown in a horizontal path. A test to determine the ceiling of an airplane is a particularly difficult one, because when the rate of climb has become small, the effect of atmospheric irregularities is relatively large. Some authorities believe that even good determinations of airplane ceiling by flight tests may be in error by as much as 10 per cent.

Weather conditions, particularly those of temperature and barometer, have a marked influence upon the performance of an airplane. It is customary, therefore, not to quote the actual results, but to calculate from them what the machine would have done if the atmospheric conditions had been average. Obviously, a fair comparison of the performances of different airplanes can be made only if they are all reduced to standard average conditions.

Approximation of Maximum Speed. For engines with propellers, maximum speed may be estimated by utilizing the fact that induced drag at high speed changes only slowly with weight. (Maximum speed varies slowly with weight of plane.)

$$\text{dhp} = \text{bhp} \times E = C_D S q \times \frac{V}{375} = \frac{0.0334 C_D d S V^3}{375}$$

$$V_{\text{mph}} = \sqrt[3]{\frac{375}{0.0334} \frac{E}{C_D} \frac{\text{bhp}}{dS}}$$

$$V = K_v \sqrt[3]{\frac{\text{bhp}}{(d/d_0)S}}$$

	K_v
For excellent planes	190
For good planes	160
For poor planes	140

The adjectives refer to speed characteristics only.

No simple expressions for rate of climb or ceiling exist.

CHAPTER XII

AIRPLANE MANEUVERS

The art of managing an airplane is not to be discovered in a book, nor can anyone expect to learn how to fly by any means other than actually doing it. It is quite possible, moreover, for a person to learn to fly with very little knowledge of the principles on which the airplane and its engine operate, just as many people drive automobiles for years with little or no idea of what goes on under the hood. Both automobile driver and airplane pilot, however, are likely to be better operators of their vehicles if they understand the natural laws to which they must conform. Complicated airplane maneuvers are hard to describe and still more difficult to understand: the simpler ones are more easily dealt with in theory as well as in practice, and some of them will now be considered.

Straight Flight. If the airplane is flying in smooth, undisturbed air, the pilot has very little to do, and this sort of flight is hardly to be considered as a maneuver at all. At cruising speed, a well-designed airplane will tend to fly straight, except for the effect of the propeller slipstream upon the rudder. The slipstream from a right-hand propeller rotates in a clockwise direction as seen from the rear, so that it strikes somewhat on the left side of the rudder and fin, since most of the area of these surfaces is usually above the thrust line. Thus it tends to push them toward the right, an action which would turn the airplane to the left, so that, to maintain a straight course, the rudder must be turned in the opposite direction *i.e.*, to the right. The amount of right rudder necessary obviously depends upon the engine power, which determines the slipstream velocity. Some airplanes are fitted with an offset fin or with a tab on the rudder which can be set at an angle to counteract this slipstream effect, relieving the pilot of the necessity of applying a constant force on the rudder pedals.

If the airplane is nose-heavy or tail-heavy, the pilot must maintain a steady pressure on the stick to prevent his craft from diving or climbing. This condition may be corrected by an adjustable stabilizer or by a tab on the elevator. A "wing heaviness," or lack of lateral balance, must be compensated for by use of the ailerons.

Turns. The combined use of the ailerons and rudder in making horizontal turns has been discussed in Chap. V under "Directional Control." To start a turn crisply and without skidding, the airplane is banked by the ailerons and prevented from skidding by the rudder. Once the turn is well under way, the outer wing tip is traveling faster than the inner; it therefore gives a greater lift and will tend to keep increasing the bank; this must be offset by returning the ailerons to zero or finally slightly opposite to hold the bank constant. To stop the turn, the plane is rolled back to neutral by the ailerons with some use of the rudder. The coordination of rudder with ailerons needed to make good turns is difficult to acquire. Designers trying to make the airplanes easier to learn to fly usually omit the rudder. Some skidding during turns must be accepted, though this may be reduced by using large fixed vertical tails or interconnecting rudder and aileron controls mechanically. Such a scheme was used on all the earliest planes built by the Wright brothers.

In an airplane with a reasonable reserve of power, it is possible to shorten the radius of turn and increase the angle of bank toward 90°, so that the wings are nearly "vertical." Under these conditions, the effects of rudder and elevator are interchanged; the latter controls the turn, and the former determines the attitude of the machine to the horizontal. For this reason, the maneuver is often called a "flipper turn." The shortness of the turn which can be executed depends upon the size and effectiveness of the horizontal tail surfaces in turning the airplane, and also upon the wing loading. When the airplane turns, the wings must exert a centripetal force, *i.e.*, an extra lift acting inward toward the center to hold the machine in the curved path. Since with a given airplane speed the centripetal force necessary varies inversely as the radius of the turn, the sharper the turn, the greater the centripetal force. If the wing loading is high, the wings cannot exert enough centripetal force to hold the machine in a sharp turn, so that it "squashes," *i.e.*, moves bodily outward from the center of the circle, even though the angle of attack is that of maximum lift. When the airplane is banked nearly 90°, it naturally loses altitude, because the lift produced by the side of the fuselage is comparatively small.

In making a turn, particularly with a low-powered airplane, it is important for the pilot to make sure that he is not holding the nose up too high and getting the airplane into a stalling attitude without realizing it. A stall in a turn is very likely to result in a spin, and if this occurs at a low altitude, the consequences may be very serious. As more power is needed for flight in a curved path than in a straight one,

only an airplane with a good reserve of power can safely attempt a climbing turn.

Glide and Dive. If, while the airplane is flying in a level path, the stick is pushed forward, the increased lift on the tail surfaces which results from turning the elevators down raises the tail and turns the nose of the airplane down. With the airplane now upon a path inclined downward, part of the weight acts along the path and enables the speed to be maintained with the engine throttled or even stopped entirely. This maneuver is called a *glide*. A stable airplane will stay naturally in a glide just steep enough to maintain the trimming speed, so that the control stick need not be held forward unless the speed desired is higher than this.

If there is sufficient altitude, the glide may be made progressively steeper, and the glide becomes a *dive*. The speed will then increase until, if the dive becomes vertical, it reaches a value at which the drag of the airplane is equal to its weight. This equilibrium speed, which is called the *terminal velocity*, is much higher than the maximum speed in horizontal flight. The terminal velocity may be calculated by inserting the lowest value of C_D, the drag coefficient, in

$$W = C_D \times 0.0334 d V_{\text{dive}}^2 S \tag{1}$$

The speed so found will be too high, for the propeller will act to retard the airplane at such high velocity. A plane with a low drag coefficient will reach a speed of 600 to 700 mph in a vertical dive.

Recovery from a dive is accomplished by pulling back on the stick, so that the resulting force on the stabilizer and elevator acts to increase the angle of attack of the wings, increasing their lift and curving the flight path upward. This maneuver, which is called a *pull-out*, may impose very high stresses upon the airplane, because the lift coefficient may be at a maximum at the same time that the speed is very much above the maximum speed in horizontal flight. The lift will be momentarily many times the weight of the plane, often six or eight; if the pull-out is violent, perhaps as many as twelve. Pursuit planes, training planes, and dive bombers are built to withstand the load resulting from the most violent possible pull-out from a terminal-velocity steep dive. The wings of other planes would collapse under such mistreatment.

Landing. In theory, landing an airplane is not a difficult maneuver. It consists of a glide at moderate speed to within a short distance of the ground, followed by a level flight just above the field with the engine idling. As the speed decreases, the angle of attack is increased so that

the machine is held off the ground until the speed has reached the minimum at which flight can be maintained. Finally, the airplane settles to the ground and rolls until it comes to a stop. If there is plenty of room, the pilot may not attempt to hold the machine off until the last possible moment, but may let the wheels touch first, making a *two-point* landing. If main wheels and tail wheel touch simultaneously, a *three-point* landing results. The practical difficulty in the maneuver lies in the necessity of close timing and accurate judgment of distance. If the machine is leveled off too high, the result is a *pancake landing*, a sharp drop of several feet when the stalling speed is reached. Slowness in leveling off leads to a hard impact against the ground, with bouncing or damage to the landing gear. To make this maneuver easier, *tricycle* landing gears are used. This is a gear with the main wheels back of the center of gravity and a third wheel in the nose. With it, if the plane is leveled off a little late, no bounce results, and no damage, unless the error is very great, since the nose wheel hits first and gently rotates the plane to proper attitude. Less skill is demanded of the pilot. The three-wheel gear is also usually easier to taxi and permits harsher use of the brakes. If the glide is begun too far from the field, the airplane will be close to the ground and will lose flying speed before a place suitable for landing is reached, while if the glide starts too near the field, the machine cannot be stopped until the landing area has been passed. A landing is always made into the wind if possible, so that for a given minimum air speed the ground speed may be least. The use of brakes on the wheels naturally reduces the length of run on the ground.

Take-off. In taking off, the throttle is opened wide at the start, and as soon as there is enough speed, the tail is lifted by the use of the elevators, so that the airplane runs along the ground on its wheels at an angle which gives low wing resistance. When flying speed is attained, the stick is pulled back, thus depressing the tail again and increasing the angle of attack of the wings, and the machine lifts off. If plenty of room is available, the airplane may be allowed to run until it lifts off naturally, without much increase in angle of attack. Normally, a take-off is made into the wind so that flying speed relative to the air may be attained at the lowest possible ground speed.

Loop. A loop (Fig. 164) may be regarded simply as a turn executed in a vertical plane. The pilot pulls back on the stick and so raises the elevator, causing a greatly increased down load on the tail. This starts the airplane rotating about its center of gravity, and at the same time gives an increased lift, which curves the flight path upward. If the speed is high enough and the controls are sufficiently powerful, the rota-

tion may be made to continue long enough to carry the airplane around a complete circle before flying speed is lost. Very often the loop is preceded by a steep glide to gain speed. If the engine power is low, the controls inadequate, or the pilot unskillful, the machine is likely to lose flying speed and "hang" at the top of the loop, so that instead of completing the evolution it "falls off," *i.e.*, slides off to the side.

The "outside" loop is executed by nosing down into a vertical dive and then going on over backward and up to a level position again. The loop takes place below the point at which the maneuver is started, and the top of the machine is to the outside of the curve. Since the maximum lift of the wings inverted is much less than that which they can exert when right side up, it is very difficult to complete the second half of the outside loop. In the ordinary loop the centrifugal force holds the pilot in his seat, but in the outside loop it tends to throw him out; while his belt prevents this, the effects of a large force directed toward his head may be very unpleasant. Making of outside loops is generally forbidden.

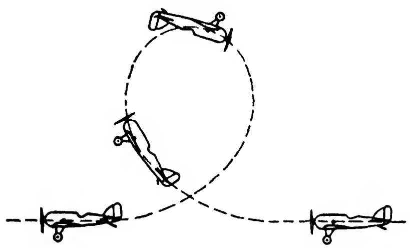


Fig. 164. A loop. (*National Advisory Committee for Aeronautics.*)

Inverted Flight. It is possible for an expert pilot, if he is firmly secured in his seat, to fly an airplane upside down for some distance, though the lift of the wings in this position is usually not enough to enable the flight path to be kept horizontal. This, and the fact that an engine fitted with a conventional carburetor will not continue to run upside down for any great length of time, limit most inverted flights to distances of a few thousand feet.

The Spin. Although the spin (Fig. 165) is a maneuver which is easily recognized if once seen, it is difficult to describe. The motion is a combined yaw, roll, pitch, and sideslip, and although from a distance the airplane may appear to be diving straight down, it actually is traveling along a flight path which is helical, *i.e.*, in the shape of a corkscrew. The radius of the helix is relatively small and may even be less than half the wing span of the airplane. The maneuver is further complicated by the fact that the angle of attack of the airplane is very high, so that the nose of the airplane is not by any means pointed along the flight path. The effect of these motions, combined with the peculiar form of the flight path and the high angle of attack, causes the tail of the airplane as a whole to go around in a circle. Unfortunately, the

explanation of the spin is complicated and too long to be attempted here. Suffice it to say that the essential characteristic of the spin is the very high angle of attack of the wings to the flight path. This may reach values not only above the stalling angle, but even as high as 60°. The spin can continue only so long as the angle of attack remains above the stalling angle, and it cannot begin until the angle of attack has reached the stalling value. If, therefore, the airplane can be prevented from stalling, it can be prevented also from spinning; even after it has started spinning, it will stop if brought out of the stall. Since the airplane when spinning is descending very steeply, the natural inclination of the untrained pilot in attempting to bring it out is to pull back on the stick to raise the nose. This is exactly the wrong thing to do. The correct action is first to check the rotation by applying full rudder against the spin, then to push the stick forward to unstall the airplane. This converts the spin into a dive, from which recovery is easy provided the plane is not too near the ground.

In the *flat spin*, as distinguished from the ordinary spin, the longitudinal axis of the airplane is not so steeply inclined to the horizontal, the radius of the helical path is smaller, the speed of rotation is higher, and the altitude lost in each turn is less. Recovery from a flat spin is more difficult than recovery from an ordinary spin. Recovery from a flat spin is made almost entirely with the rudder, since pushing the elevators down may merely increase the rate of spinning. Rudders which, in side view, project well below the stabilizer are effective in stopping flat spins.

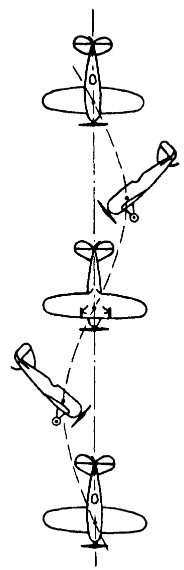


FIG. 165. A spin. (*National Advisory Committee for Aeronautics.*)

A spin of any kind begun at a low altitude is a highly dangerous maneuver, since recovery is possible only after a considerable loss of height. It is not surprising, therefore, that statistics show spins to be the cause of many of the serious airplane accidents. Since most airplanes will spin under certain conditions, pilots must be trained in spinning so that they may know how to deal with a spin should it occur accidentally. Deliberate spinning for other than training purposes belongs definitely in the class of exhibition stunts.

Roll. A roll (Fig. 166) is merely the result of a rolling motion continued in the same direction long enough for the execution of a complete

rotation of 360° about the longitudinal axis. The conclusion of the maneuver finds the airplane in its original attitude. It may be performed simply by applying the ailerons, but more often it is carried out by first increasing the angle of attack and then making the machine execute what is essentially a spin with the axis of the helical flight path horizontal instead of vertical. A combination of roll and loop gives a pilot a means of changing direction very rapidly. He may first

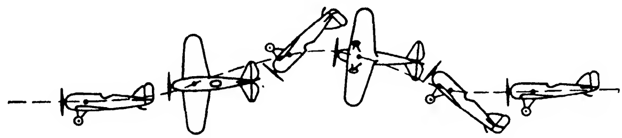


FIG. 166. A roll. (*National Advisory Committee for Aeronautics.*)

execute a half loop, and then when the airplane is upside down follow this with a half roll, thus bringing the machine out right side up and headed in a direction opposite to that at the beginning of the maneuver. This is the Immelmann turn, made famous in 1915 by the German pursuit pilot of that name (Fig. 167).

The possible maneuvers of an airplane are by no means limited to those which have been described. A properly designed airplane in the hands of a skillful pilot may be made to execute highly spectacular evo-

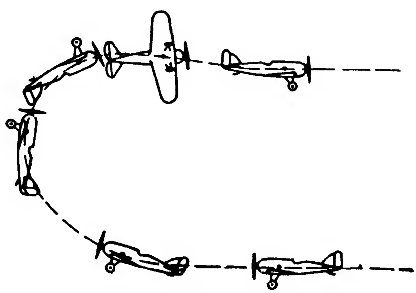


FIG. 167. An Immelman turn. (*National Advisory Committee for Aeronautics.*)

lutions, and under some circumstances it may be difficult even for the pilot to tell precisely what the airplane is doing. Such "stunts" or acrobatics, however, should be indulged in only by pilots thoroughly trained, with machines designed for this sort of work. In ordinary commercial flying, other than in training, acrobatics have little place, and the pilot's object should be to handle his airplane with the fewest possible sensations to his passengers.

Loads. In addition to the loads during pull-out from a dive, which may reach twelve times the airplane weight, maneuvers cause other loads. At the start of a dive, or when flying inverted, there will be a

down lift load on the wings, which may reach three times the weight. Rolls and spins put on the wings an unevenly distributed load of two or three times the airplane weight.

In level flight, if a vertical air current or gust is encountered, the angle of attack, and hence the lift coefficient, will be increased. The speed does not change immediately; therefore, if the gust is up, the lift is increased. A violent gust may increase the lift to four times the weight of the plane; this is the worst load the wings of a transport plane will have to withstand. If the gust is down, the load on the wings may be reversed, and a down load of one or two times the weight occur. Such a down load accelerates the plane down, and unless seat belts are fastened, throws the passengers against the ceiling—it is very uncomfortable.

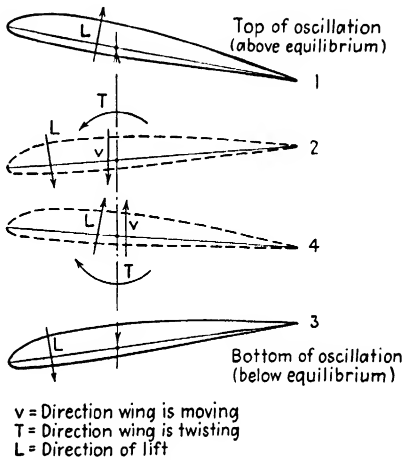


FIG. 168. Motion of wing in flutter oscillation.

In a dive at high speed, or even in level flight if the speed is very high, an oscillation called *flutter* may occur. Since this is violent and often catastrophic, the airlane designer must take precautions to prevent it. One type of flutter involves simultaneous twisting and bending of the wing. An idea of its nature may be obtained by thinking of the wing as an elastic beam. If, with the airplane stationary on the ground, the wing is deflected upward a foot or so, then released, it will vibrate up and down rapidly a few times with a gradual reduction in amplitude called *damping*. As they bend up and down, most wings twist so that the leading edge is high while the motion is upward and low while it is downward. The same vibration may occur in the air following a gentle bump. If the twisting is large and the air speed high, the changing lift load acts as negative damping (Fig. 168). Since the lift increases as V^2, above a critical *flutter speed* the air load is large enough to make the amplitude of the vibration increase rapidly, instead of damping it; the wing flutters violently and may fail after a few oscillations. Increasing the torsional rigidity of the wing reduces the angle changes that accompany the bending, hence increases the flutter speed, while designing the wing structure so that it does not tend to twist when bending removes the cause of this particular type of flutter.

CHAPTER XIII

THE AIRPLANE STRUCTURE

The twin essentials in the structure of an airplane are strength and lightness; the first without the second is useless, and the second without the first is dangerous. The structural designer must, therefore, steer a close course between Scylla and Charybdis, and only skillful compromise can lead to success. As if these difficulties were not enough, there are requirements of rigidity and low air resistance to be met, and economy in cost must not be overlooked.

In ordinary engineering structures, such as bridges and buildings, a large factor of safety is customary, and the strength is sufficient to withstand a load much greater than the heaviest which can ever come on the structure. In the airplane the need of lightness prevents this practice from being followed. The term *factor of safety* often used in connection with airplanes is a misnomer; the correct term is *load factor*. A factor of safety is based on maximum possible load, and if a structure has a factor of safety of four, then the greatest load which can ever come on it is only one-fourth, of that required to break it. A load factor, on the other hand, is based on normal load, so that if the structure of an airplane is designed for a load factor of seven, it is just strong enough to carry a load seven times that which comes on it in steady horizontal flight. It has already been pointed out, however, that in acrobatics the loads on various structural members may be much higher than those imposed in uniform level flight. If an airplane designed for a load factor of seven were pulled out too sharply from a very fast dive, the load on the wings might be more than seven times that in normal flight, and so cause a failure. The airplane pilot must therefore limit his maneuvers to those which do not impose loads beyond the strength of his machine. For example, airplanes are placarded for the maximum allowable speed in a dive, and the pilot must never permit the plane to exceed that speed. The designer must provide sufficient strength for any maneuver which the airplane may legitimately be called upon to execute. An airplane for acrobatics, accordingly, has a load factor of twelve, and a large slow commercial machine one of four.

Rigidity in an airplane structure is almost as essential as strength,

for excessive deflection or bending under load may lead to a loss of control, with consequences as serious as those of a definite breakage. As already discussed, lack of rigidity may also permit the development of *flutter*, a motion which arises when the deflection of a part of the structure causes the air forces on it to change in synchronism with its natural period of vibration. Flutter is most often experienced in wings and in control surfaces.

In seeking strength and rigidity, the primary essential of light weight can never be lost sight of, for every pound of increase in the weight of airplane structure means a corresponding decrease in the useful load which the plane can carry and, consequently, a decrease in military effectiveness or in earning power. Low air resistance is likewise of great importance, for an increase in drag leads directly to a loss in performance, or, if the power plant is enlarged to maintain the performance, to a reduction in carrying capacity.

The limited margin of safety permitted by weight limitations makes it necessary to proportion the members of the structure so that each may bear its proper share of the load in every anticipated condition of flight. The security of the structure as a whole is no greater than that of the member whose strength is least in proportion to the load imposed on it. To attain this uniform and adequate structural safety, it is essential to calculate what load each part may be called on to carry under every condition of flight to which the airplane may properly be subjected. Such a determination of loads is called a *stress analysis*. The method employed is based entirely upon the principles of physics and mechanics, and is essentially the same as that used in calculating the loads in the various structural parts of a bridge. After the worst load to be expected in a member has been figured, the size and shape of that member are made such as to give it a margin of strength which is sufficient but not excessive. All this is a complicated process.

The history of more than forty years of development and refinement in airplane construction is very interesting, and to it a whole book could be well devoted. In this chapter, however, space permits consideration only of types of construction that are now in use. Since different parts of the same airplane may exemplify diverse methods of construction, it is most convenient in discussing the subject to deal with the several parts of the airplane in order, rather than to describe various airplanes completely.

WING CONSTRUCTION

The wing of the airplane must withstand the most severe loads. For its design and construction the best skills of the engineer and mechanic

are needed; otherwise the wing will be too heavy or possibly fail in flight. When the wing loading (weight per square foot of wing area) is low, not over 10 or 12 lb per sq ft, the lightest wing structure is still the traditional one: a rigid frame with fabric covering. As the wing loading is increased, however, it is increasingly difficult to make the framework rigid and to attach the fabric securely to it, particularly if the wing is cantilever. Both troubles are lessened by changing to metal-covered wings. This covering may be thin and may buckle on the top when the wing bends upward, or it may be thicker with stiffeners to prevent the buckling. The latter case is more common, with the skin supplying an important contribution to the strength of the structure; this is called *stressed-skin* construction. The portion of the total load supported by the cover varies from only a small part when the skin is thin to almost all when the skin is heavy and the inner frame merely maintains the shape rather than supporting the skin. This variety is *monocoque.*

Fabric-covered Wing. The fabric covering is finely woven cotton cloth with about 90 threads per inch in each direction. The breadths of cloth, sewn together with double-locked seams, start at the trailing edge, run around the wing over the leading edge back to the trailing edge, where the ends are stitched together. The fabric is stitched and tied to the wing ribs. The covered wing is painted and sprayed with *dope.* Dope is a solution of *cellulose acetate* or *nitrate* in *acetone.* The acetone evaporates quickly leaving the fabric impregnated with a plastic film that makes it airtight, waterproof, and besides—stronger. The dope also shrinks the fabric so that the cover is as tight as a drumhead. Next, tapes are doped over all seams and stitching to make the surface smooth.

The framework of a fabric-covered wing may be wood or metal or a combination. The typical arrangement is the same: two principal spanwise beams called *spars,* separated by rather closely spaced light ribs; at intervals a heavy rib or often a steel tube between the spars divides the span into *bays;* in each bay are crossed diagonal wires or swaged tie rods. Together the spars, tubes, and wires form a rigid *truss* in a plane parallel to the wing chord, thus preventing chordwise loads, which may act in either direction, from distorting the wing (Fig. 169). All fabric-covered wings have external bracing, but the spars provide the stiffness to resist the lift load between strut support and fuselage.

The wood used for spars or ribs is clear straight-grained spruce or *plywood.* Plywood is a wooden sheet composed of at least three thin

layers of wood glued together with waterproof glue or resin. The outer layers are often birch or other hardwood, the inner plies softwood. The direction of the grain is crossed in alternate plies. Metal ribs or spars are usually high-strength aluminum alloy, duralumin.

Wooden spars are either I or rectangular sections of spruce, or box section with spruce top and bottom pieces, *flanges* or *caps*, and plywood sides, *webs*. Metal spars are rolled or extruded I sections or may be built up of plates and T sections riveted together. For small airplanes, spars are built as simply as possible; trusses made up of many small

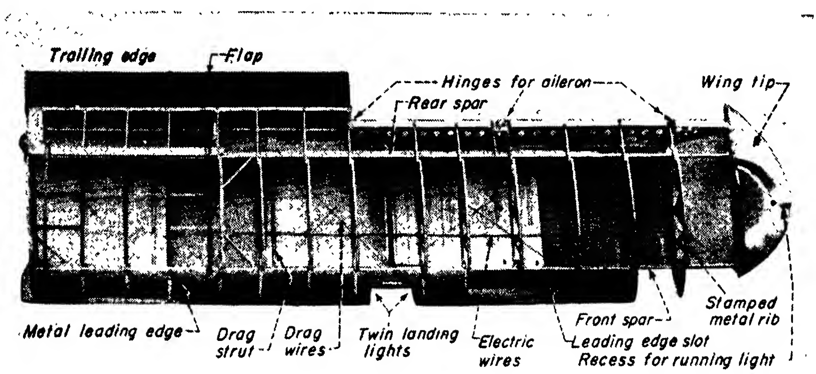


FIG. 169. Structure of fabric-covered wing of voyager. (*New England Aircraft School.*)

parts are seldom used, but plates or I-beam webs may have lightening holes cut in them.

The ribs are thin, light members that form the contour of the wing section and transmit the air loads from the fabric to the spars. Simplest wooden rib is a single layer of plywood with a spruce *cap strip* around the edge. Somewhat lighter is a rib made up of spruce strips with plywood gussets. A wooden rib is surprisingly strong; one 9 ft long weighing only 15½ oz has withstood a distributed load of 940 lb. For most small airplanes, ribs are simple stampings of duralumin with lightening holes (not necessarily circular). Edges of lightening holes and contour are flanged to stiffen the rib. The fabric fits directly on the top and bottom flanges. Because of the difficulty of fabricating many small parts, metal ribs for fabric-covered wings are seldom built like a truss.

To maintain more exactly the contour of the airfoil at the leading edge, a strip of plywood or metal is often bent around the leading edge forward of the front spar. This reinforcement also helps support the high local loads that occur.

Occasionally the entire surface of the wing is covered with plywood, either under the fabric or with fabric omitted. The plywood may be put on in strips or may be made or molded in special forms to the exact shape of wing.

The spars of a fabric-covered wing cannot be made deep enough to sustain the lift load; hence such wings are externally braced. A typical braced monoplane has the wing at the top of the fuselage with a single V strut extending from the fuselage to a point about 60 per cent of the wing span (Fig. 170). Such struts are usually streamline section

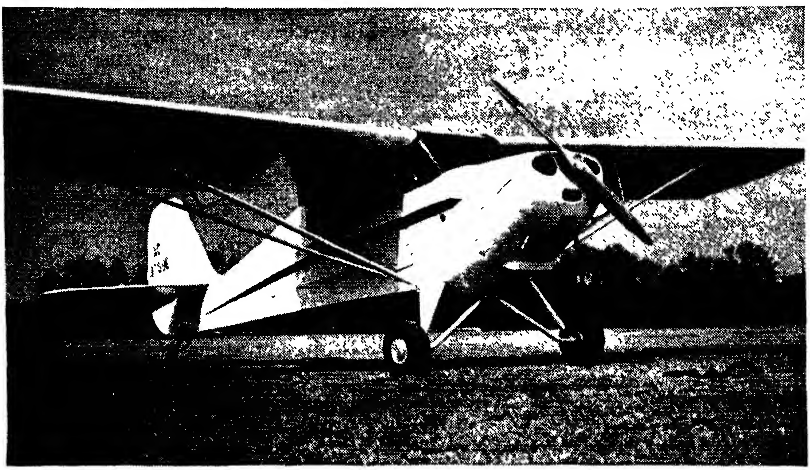


FIG. 170. Monoplane with wing braced by V struts. (*Aeronca Aircraft Corporation.*)

steel or duralumin tubing. External bracing on biplanes is more extensive, usually including an interplane strut and two pairs of streamline wires, one to support the lift load in normal flight, the other pair to prevent collapse in inverted flight or landing (Fig. 2). The fuselage, spars, wires, and interplane struts combine to form two very stiff trusses that are linked together by the stiffness of the interplane struts and the fuselage.

Metal Wing. Since the lightest practicable metal covering is so much heavier than fabric, about 24 oz per sq yd instead of 9 oz for the fabric, mere replacement of the fabric by metal does not make an economical structure. Therefore the metal wing covering is almost always made a part of the primary structure of the wing.

The arrangement of the metal structure varies greatly in different sized wings and those designed by different engineers. Typical perhaps is this scheme: two or more main spars, rather widely spaced ribs,

fairly heavy cover sheet between the spars and around the leading edge, lighter skin on the trailing edge behind the rear spar, the skin reinforced by spanwise stringers, the whole riveted rigidly together.

Types of spars include built-up I beams with plate webs and extruded T-section flanges. The plate web is sometimes lightened by round or oval holes, often flanged on the edge, and is reinforced by angles. Instead of the T sections, the plate may be flanged to provide attachment to the skin. On larger planes the spar is sometimes a truss. Top

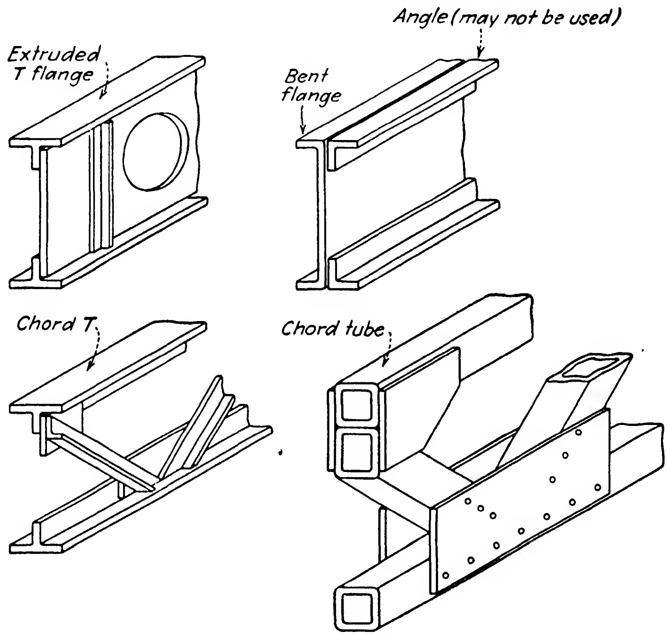


FIG. 171. Sketches of metal spars.

and bottom *chord* members or *caps* may be channels made of bent sheet or extruded T's with vertical or diagonal braces of channel or angle. In other cases, chord members may be tubes, usually square in section. For example, on a B-17 bomber the chord members in the central part of the wing are aluminum-alloy tubes, 2.7 in. square with wall $\frac{1}{2}$ in. thick. This provides a very strong spar but riveting of the skin and other parts to the tubes is difficult and requires many man-hours of labor. The rivet cannot pass wholly through the tube but only through the wall and must be held, while being driven or pounded into place, by a backing piece that fits inside the tube.

Typical spar sections are sketched in Fig. 171. In Fig. 172 is shown

an inner wing spar of a Navy Corsair fighter. This shows clearly the complexity needed for such a highly loaded wing. At the left are heavy forgings, forming hinges for the outer wing panel, which can be folded upward so that the plane occupies less room on the deck or eleva-

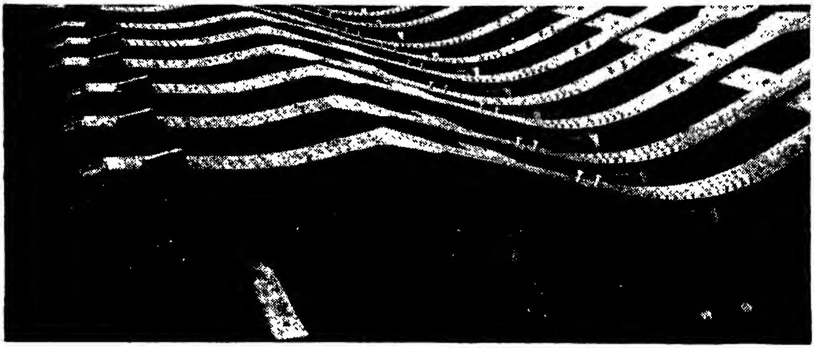


Fig. 172. Center section spar of Corsair. (*Chance Vought Aircraft.*)

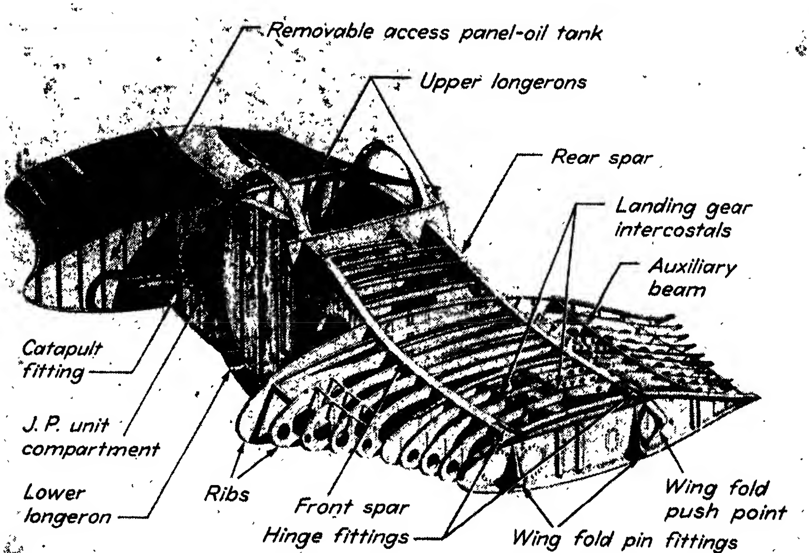


Fig. 173. Inner wing of Phantom. (*McDonnell Aircraft Corporation.*)

tor of an aircraft carrier. Figure 173 is a skeleton view of the inner wing structure of another Navy fighter, the Phantom. This plane is driven by two turbojet engines, and the spars pass completely around them (marked J-P Unit compartment). Heavy *bulkheads* connecting right and left spars across the fuselage are clearly shown.

The wing skin varies from a few hundredths of an inch thick on small planes with light wing loadings to $\frac{3}{16}$ in. or more on large planes or heavily stressed fighters. In some cases, to improve the surface smoothness, even thicker skin is used with less internal structure. When the skin is thin, it must be stiffened to prevent buckling. Typical stiffeners are Z or hat sections; the latter is more symmetrical but requires two rows of rivets and leaves a closed passage. Closed passages form potential sources of corrosion trouble. When particularly extensive stiffening is needed, an inner skin corrugated and riveted to the outer does duty as stiffeners and heavier skin. Rivets on the outer surface are usually *countersunk*, since even very shallow projecting heads would cause a large increase in drag of the wing (as much as 30 per cent). When the skin is thin, the metal cannot be countersunk like a plate on a steamship but must be *dimpled* to provide for a strong rivet. For extremely smooth wings on high-speed airplanes, the heads of the rivets are ground off flush after being driven.

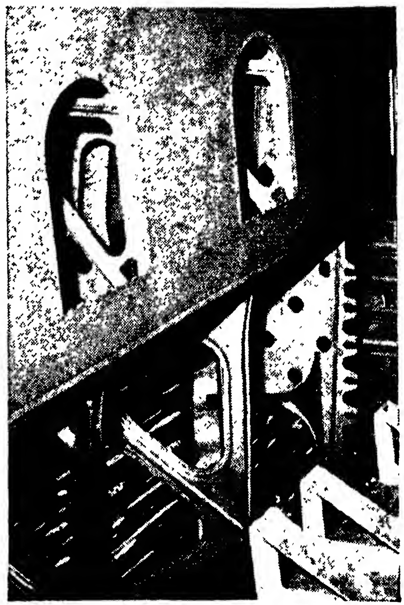


FIG. 174. Wing construction. (*Lockheed Aircraft Corporation.*)

The ribs or chordwise frames of the stressed-skin wing also must maintain the shape of the airfoil section. Most ribs are stampings with flanges to upper and lower skin in place of separate cap strips. Some have flanged lightening holes, while on others the sheet is cut to truss-like members usually with crimped edges for stiffness. Such ribs are shown in Fig. 174. The wing, part of that for a Constellation, is supported vertically. The odd triangular frames in the right foreground are not part of the wing. At the top of the figure is bottom skin back of rear spar; through the inspection holes portions of ribs are seen. The flange at top of open part is the rear spar. Between it and the front spar (below margin of picture) are heavy ribs. At left the corrugated subskin of upper surface of wing between spars shows clearly. Sometimes the ribs are made of separate pieces riveted together, but if

more than a few planes are to be built alike, it is more usual to make a die, perhaps even a temporary one of cast metal, single with rubber mat backer, and stamp the ribs in a hydraulic press (Fig. 175), thus avoiding assembly of small pieces of metal. (In the figure the top and bottom dies are in place to make a curved door panel, also for the Constellation.)

FIG. 175. Hydraulic press for stamping parts. (*Lockheed Aircraft Corporation.*)

FUSELAGE CONSTRUCTION

Broadly, just as in case of the wings, airplane fuselages are divided into two groups, fabric-covered or stressed-skin. Fabric-covered fuselages are found only on smaller commercial airplanes or (sometimes) on military trainers.

Fabric-covered Fuselages. Typically the framework of a fabric-covered fuselage is of welded steel tubing. At the corners are *longerons* that form chord members of side and top and bottom trusses. The cross members are lighter tubes welded in place. On some light planes there are only three longerons in back of cockpit or cabin (Fig. 176). The lighter colored members are the steel-tube structure. Plywood formers support wooden strips to which the fabric is fastened. At the front, cabin lining is in place, also wooden members to enclose windows and doors. Soundproofing such as rock-wool or spun-glass blankets

will be placed between the outer fabric and the cabin lining. The workman provides an idea of size.

Metal Fuselages. Sometimes metal-covered fuselages retain the idea of four principal longerons starting at the front and extending to the tail; in other designs there are no longerons except near wing roots or engine-support points in single-engine airplanes. In such cases, to the rear of the strong frames or bulkheads at the wing spars, the fuselage primary structure, especially in larger planes, consists only of

FIG. 176. Steel-tube fuselage. (*Aeronca Aircraft Corporation.*)

metal skin reinforced with many longitudinal stringers that may be Z or hat section, with cross-sectional shape maintained by heavy frames or rings and widely spaced extra-strong frames or solid bulkheads. Such a design is called monocoque. Figure 177 is a photograph of three sections of the fuselage of a large transport, the Constellation. These sections will next be riveted together. Longitudinal stiffeners are Z's, all the same without heavy longerons; transverse rings are channels with the outer flange curled to give added stiffness. The interior of the same fuselage is seen in Fig. 178 (the platform is temporary). Around the window at the left are heavy frames to prevent this opening from weakening the structure. The size of the frame illustrates the diffi-

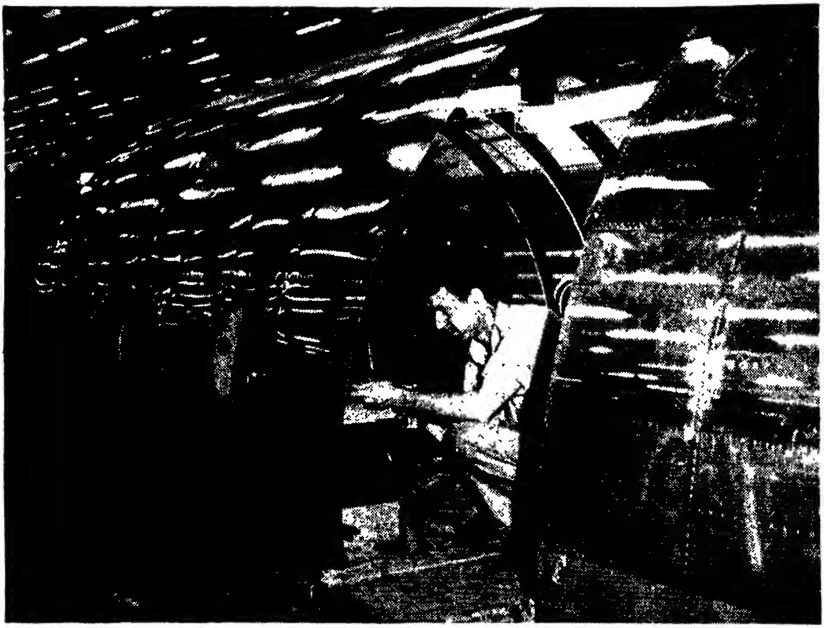


FIG. 177. Sections of fuselage of Constellation. (*Lockheed Aircraft Corporation.*)

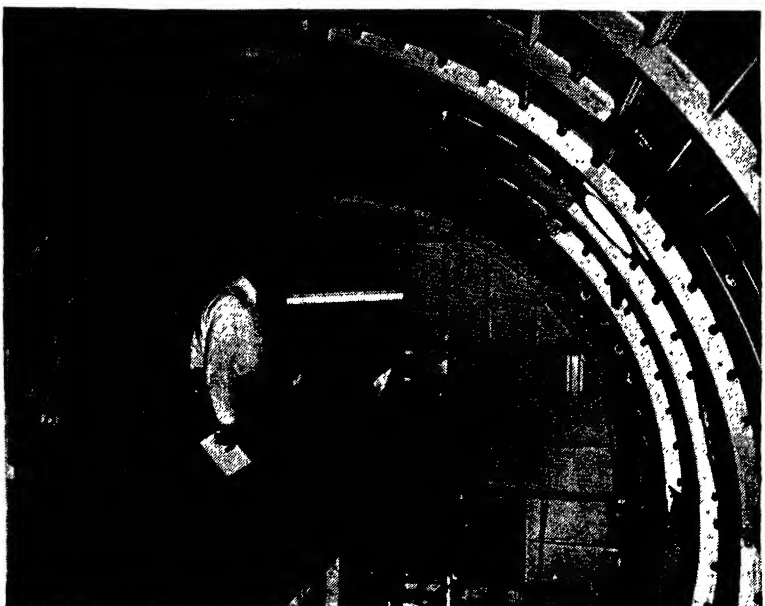


FIG. 178. Interior of Constellation fuselage. (*Lockheed Aircraft Corporation.*)

culty of maintaining strength of a monocoque structure when large openings are needed. For example, very heavy reinforcement is required around the bomb bay in bombers. The floor in Fig. 178 is for the passenger cabin; it is not usually part of the structure. The cross sections of the fuselage are circular; this is because the fuselage of the Constellation is *pressurized* to make passengers more comfortable and allow flight at higher altitudes. Inside pressure may correspond to 8,000 or 10,000 ft while the plane is flying at 25,000 ft. The excess internal pressure is $4\frac{1}{2}$ lb per sq in.; this makes a bursting load of 3,700 lb on a section of skin 1 ft long, which it must withstand in addition to the air and other loads. Help is received from stiffeners and rings. If the cross section were not circular, it would distort toward a circle.

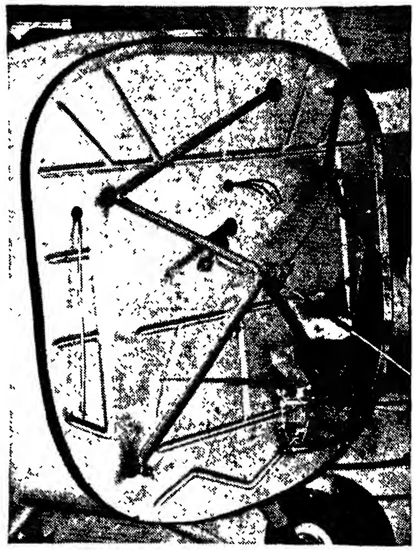


FIG. 179. Firewall of light plane. (*Aeronca Aircraft Corporation.*)

Nacelles. Nacelles for mounting of engines along the wing are built like small-sized fuselages. For tractor engines, the nacelle is supported largely by the front spar, though it may be faired back to the rear spar or even beyond the trailing edge of the wing. The forward portion has heavy framework covered by stiffened skin. Rear portion is usually monocoque. Sections of the skin may be fitted as demountable panels. The nacelle must preserve the continuity of the wing's leading-edge structure; hence wing skin is attached firmly to the nacelle skin and frames.

Fire Wall. Separating the rest of nacelle or fuselage from the section containing the engine itself is the fire wall. This is either a single sheet of heavy steel or a sandwich of lighter metal with asbestos filling. To guard against failure of the fire wall to prevent minor power-plant fires from spreading, the fire wall is made as nearly solid as practicable with close-fitting guards around the few openings required for controls. An example of the tightness of the fire wall even in a light airplane is shown in Fig. 179; controls for the small engine are extremely simple. Gasoline tanks must be back of the fire wall; oil tanks for engines with

"dry" crankcases are often ahead, though lubricating oil can sustain a fire once it is started. Nacelles and engine sections on transport airplanes are fitted with fire-extinguishing pipes, generally using carbon dioxide gas, but unless the large airflow through the cowl can be greatly reduced quickly, the task of the extinguisher is almost impossible.

Engine Mount. Though not part of the structure, the *engine mount* bolts directly to it. To hold these concentrated loads, the front of nacelle or fuselage must be specially designed. If no longerons are fitted, extra stiffening to distribute the load into the skin must be arranged. The mount for a radial engine is generally welded steel tubing regardless of the type of fuselage construction. The simplest pos-

FIG. 180. Assembly of Constellation. (*Lockheed Aircraft Corporation.*)

sible steel-tube mount is shown in Fig. 179. Here the mount is bolted directly to the front ends of the four longerons, while the engine is bolted to the mount by four other bolts through rubber bushings. For in-line or V engines, the mount is sometimes forged or built-up channels extending from the main fuselage or nacelle structure. In Fig. 180 a scheme to permit easy access to the engines by using "orange-peel" cowls is seen.

CONSTRUCTION OF OTHER AIRPLANE PARTS

Control Surfaces. Fixed control surfaces are usually similar in construction to the plane: spars, stamped ribs, metal covering on stressed-skin airplanes, steel tubes or angles with fabric cover on planes with steel-tube fuselages. In Fig. 176 the frame for the fin is an extension of the fuselage. Movable surfaces generally have light metal frames, often with a D spar; cover may be fabric or lightweight metal (Fig. 181). The notch at the right in Fig. 181 is for the rudder trim tab. With the D spar, the center of gravity of the surface is forward nearer

the hinges (in high-speed airplanes, the center of gravity of the control surface should be on or in front of the hinge line to help prevent flutter). On small airplanes, rudder and elevators are sometimes made of ribbed stampings with no internal frames. The surfaces are moved by cables or push rods attached to horns on the surface.

Control-operating Mechanism. The arrangement by which the pilot operates the control surfaces has already been described in a general way in Chap. V.

For transmitting the movements of the controls in the cockpit to the surfaces themselves, extra-flexible steel cables are ordinarily employed.

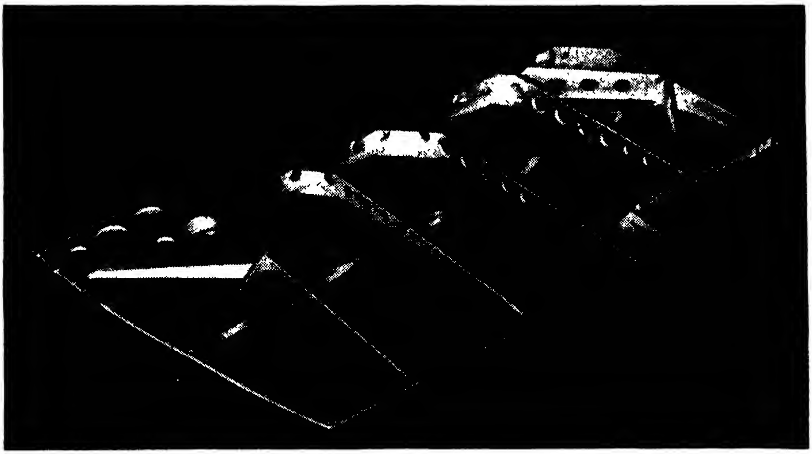


FIG. 181. Riveted duralumin rudder skeleton. (*Northrop Aircraft, Inc.*)

To avoid interferences, these cables may have to turn a good many corners, and at these points they run over grooved pulleys, which are provided with sheet-metal guards to ensure that no cable can slip off its pulley. To make the control system operate with the least possible friction, the pulleys, and often many of the other moving parts, are mounted on ball bearings. A correct adjustment of the tension in the control cables is essential and is generally made possible by the use of a *turnbuckle* in each cable. This device consists of a bronze barrel with oppositely threaded ends into which are screwed steel shanks. The end of each shank is formed into an *eye* or *clevis* for attachment to the cable or to some other part of the control system. By turning the barrel in the proper direction, the cable may be drawn up or slacked off.

In other airplanes, connections from the control surfaces to cockpit controls are made wholly or partially by push rods or tubes with ball-

bearing bell cranks at corners. Occasionally torque tubes are used to move ailerons.

Proper operation of the controls is essential to the safety of the airplane in flight, and great care is therefore necessary in the design and construction of the control system. Strength must be ample at every point, and the installation must be such that jamming cannot result from loose objects getting into the controls or from interferences between any part of the control system and the rest of the airplane.

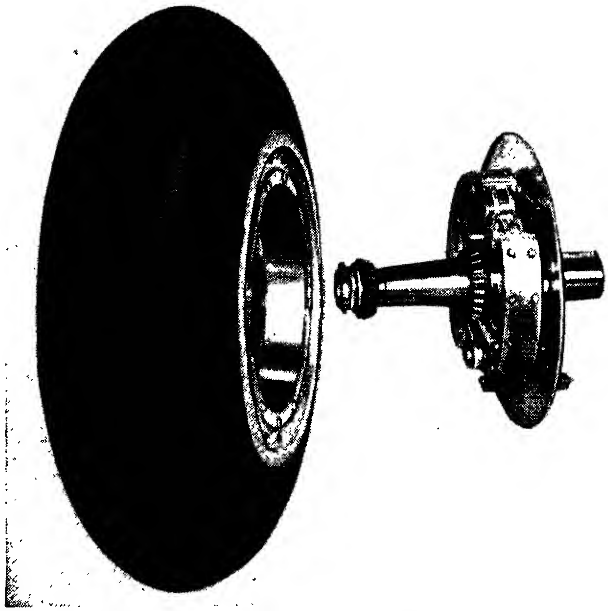


FIG. 182. Airplane wheel, tire, and brake. (*Bendix Products Corporation.*)

Landing Gear. Conventional or older type landing gears have two main wheels located slightly in front of the center of gravity of the airplane and a third small one at the tail. Tricycle landing gears have the two main wheels just behind the center of gravity with the third at the nose. Except for light airplanes, most current designs have tricycle landing gears, with main wheels retracting into wing or nacelle and nose wheel into the fuselage.

Tires and brakes are not unlike those of automobiles. Most brakes are hydraulically operated, usually controlled separately by pedals below the rudder pedals. The separate control permits the pilot to steer the airplane while taxiing on the ground by applying the brake to

retard one side or the other; though on some tricycle and most conventional landing gears, the third wheel is also steerable. Use of brakes permits a shorter turn.

Wheels are aluminum or magnesium alloy, almost all hub, with built-in brakes (Fig. 182). Parts of another brake for a small plane are shown separated in Fig. 183. Disc 3 is held in wheel by notches on edge; hydraulic cylinder 1 is fixed; piston 7, fitting in cylinder 1, sealed by ring 6, clamps disc between brake pads 2 and 4 when hydraulic pres-

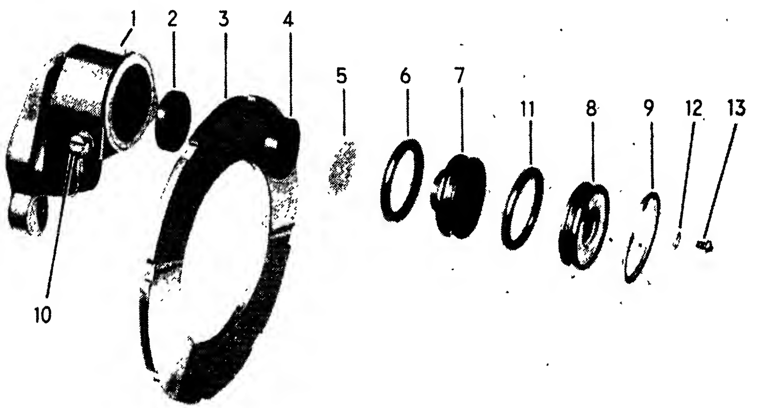


FIG. 183. Parts of brake for 6.00-6 wheel. (*Aviation Products Division, The Goodyear Tire and Rubber Co.*)

sure is applied by pedal or valve. The wheels fit on an axle that is spring-supported to the airplane fuselage or wing. The spring may be steel or air or rubber discs or shock chord. Rebound is prevented and landing shock cushioned by *shock absorbers*, usually hydraulic; if shock chord or rubber discs are used, the friction between layers is relied on to prevent excessive rebound. Only a few light airplanes still use rubber shock absorbers. In many cases the initial shock is taken by the hydraulic cylinder alone, oil being forced through a small orifice. The work done heats the oil, but a few degrees rise in temperature is the equivalent of a large amount of work. If it is desired that the load on landing be reduced by the shock absorber to not more than three times the weight of the airplane, the travel of a well-designed shock absorber must be 4 in. for each foot of drop estimated for the landing. A vertical velocity of 8 ft per sec is equivalent to a 1-ft drop, while 16 ft per sec corresponds to a 4-ft drop.

The axle may be hinged to the fuselage near the center with a shock-absorbing strut supporting it vertically and horizontally (Fig. 170). Such a gear is fixed. When the gear is retractable, the axle is usually held rigidly by the shock strut (Fig. 184); vertical and twisting loads are held by the shock strut, which is restrained from folding back by the retracting strut. This gear retracts straight back, the wheel rotating through 90°, lying flat into the wing and closing the doors behind it. Another example of a retractile gear (Fig. 185) is for a large airplane, the famed B-29; this dual wheel retracts straight back into the inner

FIG. 184. F4U-5 Corsair. (*Chance Vought Aircraft.*)

nacelles. In other cases, the wheels retract sideways into the wing or fuselage.

Landing gears are treated roughly and must be sturdy mechanisms. If damaged, replacement must be reasonably easy. Attachment to the plane should be such that in case of extra-hard landings, the landing gear fails and absorbs much energy without damage to the rest of plane. Retracting mechanisms are hydraulic jacks or electric motors, sometimes with hand auxiliary schemes. Retraction and extension must be swift and certain; warning devices call the pilot's attention if he fails to extend gear before landing; these may be actuated by position of throttle or control.

When the wings of an airplane are extremely thin, there may not be room enough in the wing to enclose the wheels. The wheels are reduced to two (dual), a bicycle gear, on the center line of the fuselage

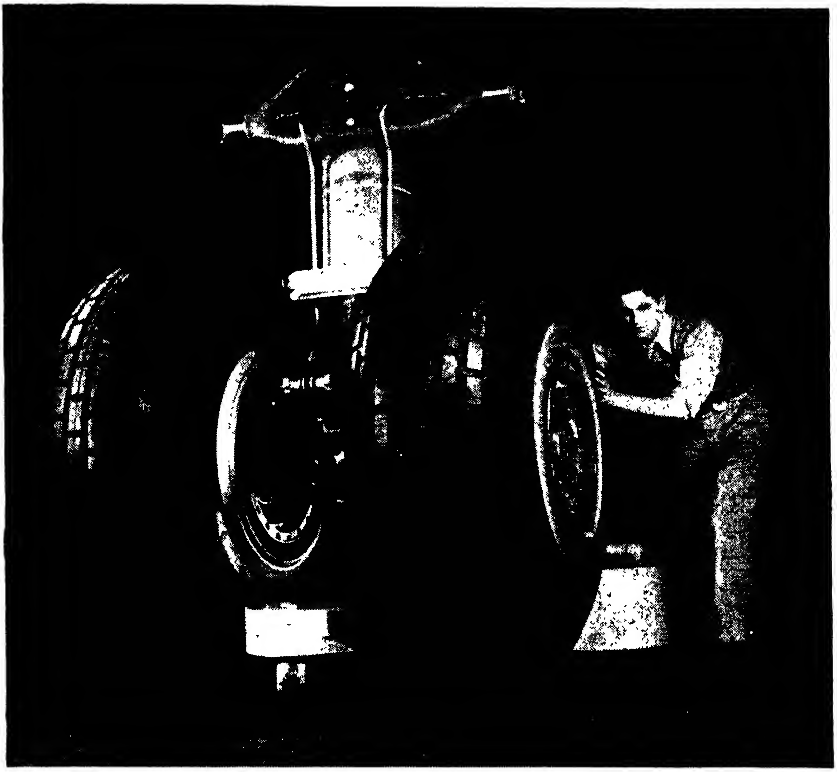


FIG. 185. Dual wheel and landing shock strut of B-29. (*Boeing Airplane Co.*)

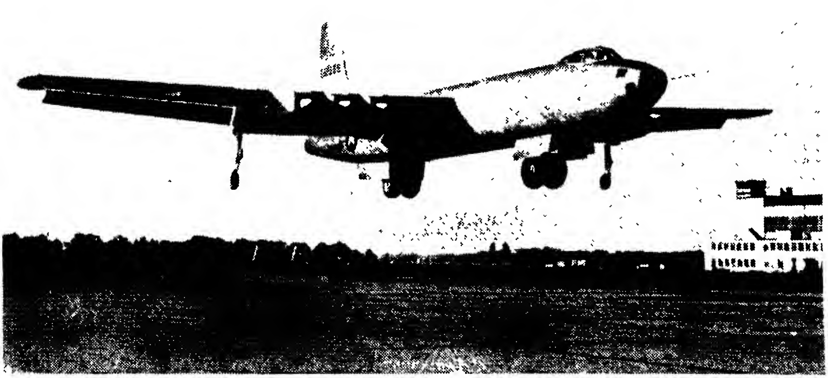


FIG. 186. Bicycle landing gear, XB-48 jet bomber. (*The Glenn L. Martin Co.*)

(Fig. 186); auxiliary small wheels near the wing tips touch only after the plane is nearly stopped.

Another gear, or special wheels, casters to permit landings with a wind across the runway. The pilot makes a normal landing directly along the runway holding the plane "crabbed" relative to the ground sufficiently to prevent drifting sideways off the landing strip. When the wheels touch they caster and line up with the direction of the run-

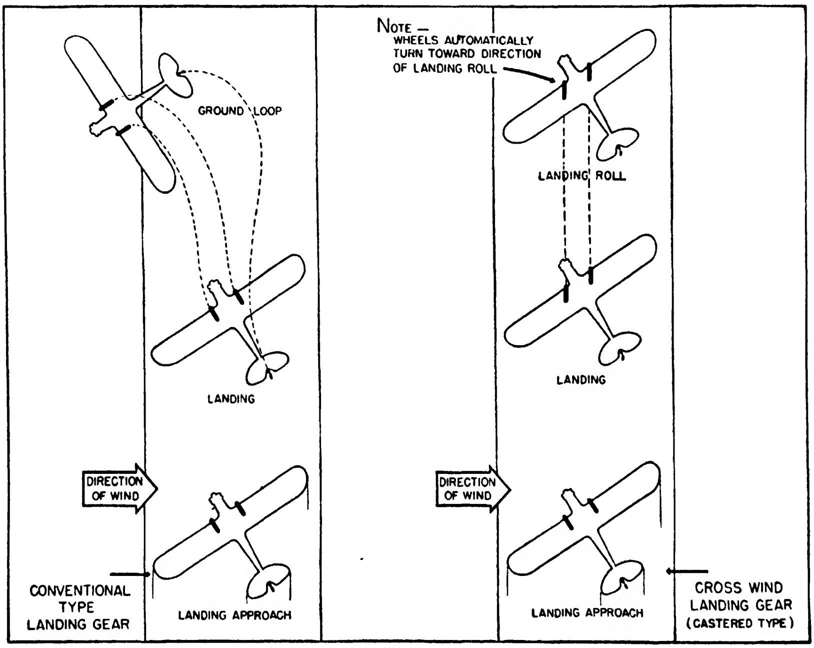


FIG. 187. Schematic landings with plain and castering wheels. (*Aviation Products Division, The Goodyear Tire and Rubber Co.*)

way (just as a caster on a piece of furniture follows its motion) (Fig. 187). Landing gears on very early airplanes, *e.g.*, the famous cross-channel Bleriot, were castering. The present development is sponsored by the Civil Aeronautics Administration. A sketch of the wheel (Fig. 188) shows the wheel rotating on the axle on roller bearings and turnable through $\pm 25°$ about the kingpin. Compensating cams, shimmy dampers, and springs are needed to hold wheel central in flight, to prevent it from "shimmying," and since the kingpins are not vertical, to prevent the plane from "plopping" over to one side or other. Single-disc brake and actuating cylinder are shown.

Airplane Materials and Protective Coatings. The principal materials used for airplanes are wood, fabric, steel, and aluminum alloy.

The woods used are spruce and plywood, the latter made of birch or spruce. Airplane spruce is smooth, straight-grained, with visible growth lines. It weighs about 27 lb per cu ft and a section 1 in. square will hold 9,400 lb.

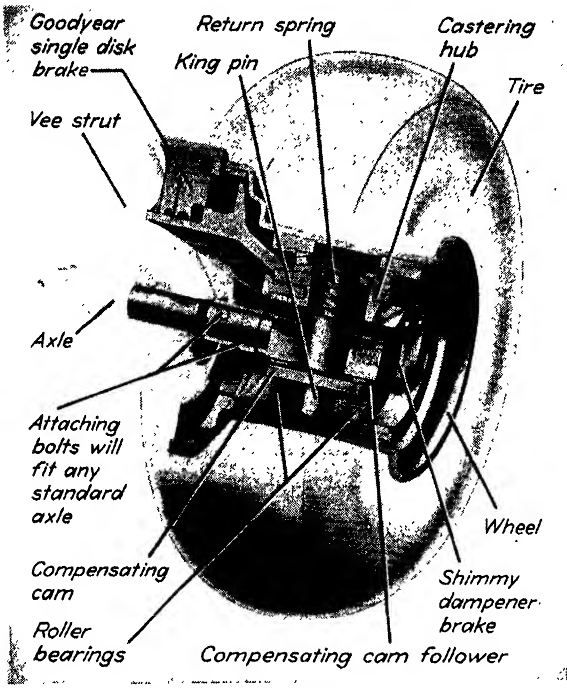


Fig. 188. Phantom sketch of castering wheel. (*Aviation Products Division, The Goodyear Tire and Rubber Co.*)

The wood is carefully dried, and, to exclude moisture, all wooden parts receive several coats of *varnish*. The base of the varnish may be natural resin or a synthetic resin like *bakelite*.

The fabric covering is cotton, strengthened and protected by dope. Sunlight weakens both the dope and the fabric, so the last coats of dope may have pigment in them to exclude the light, or a coat of pigmented varnish may be put on the wing.

For main structural members, steel is used as tubing or as sheets. Steel weighs 490 lb per cu ft. *Mild carbon* steel tubing is used for fuselages and control surfaces. Its strength is 55,000 lb per sq in. A

stronger alloy steel, *chrome-molybdenum* steel, is used for fuselages and control surfaces. Its strength is 80,000 lb per sq in. The same material may be used *heat-treated* for axles; its strength is then about 150,000 lb per sq in.

These steels must be prevented from rusting by careful painting. The inside of tubing is usually covered with a film of heavy oil. Small steel parts may be plated with cadmium or chromium.

Stainless-steel sheet has occasionally been employed for ribs and spars. Stainless steel contains 18 per cent chromium, 8 per cent nickel, and the rest iron; its strength as used is 185,000 lb per sq in. No protection for this steel is required, as it will not rust. It has not been widely used for stressed-skin planes, since the parts would be too thin if made light enough.

Most used of all aluminum alloys, from which structural parts, either sheet or extruded section, are made, are those usually called rather loosely *duralumin.* These have the peculiar property of hardening slowly after heat-treatment so that rivets may be squeezed in, sheet bent to shape, etc., with the metal soft; then in about 8 hr it becomes hard and much stronger. The alloys weigh about 175 lb per cu ft; strength and properties of several are given in the following table:

Alloy	17ST	24ST	75ST
Principal ingredients			
Copper	4 %	4½%	1½%
Manganese	½%	½%	
Magnesium	½%	1½%	2½%
Zinc	......	......	5½%
Aluminum	94 %	93 %	89 %
Strength, lb per sq in	60,000	69,000	81,000
Stretch	20 %	16 %	10 %

Low stretch indicates poor ductility and difficulty of forming; hence the 75ST alloy is used mostly as sheet where small curvature is needed. Some further increases of strength, but at expense of loss of ductility and increased susceptibility to corrosion, may be obtained by "aging" at elevated temperatures for a few hours.

Pure aluminum is nearly rustproof, but duralumin corrodes very rapidly, particularly near salt water. It must be very carefully painted to prevent moisture from reaching it. The first coat usually contains something that actually delays the rusting, such as *zinc chromate;* the

outer covering may be varnish, usually bakelite, with aluminum powder in it.

To avoid the corrosion difficulties, *alclad* sheets may be used. This material is a sandwich of a thick layer of strong alloy between two very thin slices of pure aluminum. Most of the all-metal airplanes are now built of alclad sheets. These may be painted or lacquered in colors to suit the owner's fancy, but the alclad requires no corrosion protection.

Plastics, by which are meant materials formed of synthetic resin such as bakelite reinforced by inclusion of some wood, spun glass, or other fiber, have great possibilities for quantity production of airplanes. The reinforcing is an evil required by the low strength of the resin itself. Such materials may be made with very smooth surface, can be made moistureproof, and will not corrode. The plan is that entire wings or fuselages may be made in a mold, therefore quickly, and, if a large number are made, cheaply.

CHAPTER XIV

THE SEAPLANE AND THE AMPHIBIAN

Where smooth water is more readily available than level ground, a *seaplane*, able to land upon and take off from the water, has obvious advantages over the more common *landplane*, which operates only from the ground. The term *seaplane* is a general one applied to all airplanes designed to float on the water and is synonymous with *hydro-airplane*, a word too clumsy ever to have come into common use. A *hydroplane*, however, is a boat which skims on the surface of the water and is not an airplane at all.

The *amphibian* airplane, or, more often, simply *amphibian*, is a seaplane to which has been fitted a retractable landing gear allowing it to land on an airport as well as alight on the water.

Seaplane Types and Arrangements. Seaplanes are divided into two principal groups: *float seaplanes and flying boats.* The float seaplane is essentially a landplane with floats substituted for the wheels, as shown in Fig. 189, the same plane with wheels and floats. This plane, a single-seater, is one used by the scouting cruisers of a fleet to extend the sight range of the fleet miles beyond the horizon. For this service as a seaplane, it is catapulted from the deck, and on its return lands in the wake of the cruiser. The single large float provides support during landing and take-off, while the smaller tip floats are needed only to prevent the seaplane from tipping over when at rest on the water. They are otherwise a nuisance, since they add to weight and drag of the plane and are liable to damage when landing on rough water.

An alternate float gear (Fig. 190) has two main floats. This type of gear may be attached to the fuselage of a high-wing monoplane, thus converting it to a seaplane. This is an advantage for the twin-float gear, since the wing would require reinforcement to support the tip floats needed by the single-float arrangement. Twin floats provide somewhat easier access to the cabin. However, the twin-float gear often is heavier and adds more drag than the single-float gear and is more liable to damage in rough water.

The flying boat differs from the float seaplane in that the hull required for landing, flotation, and taking off is combined with the nor-

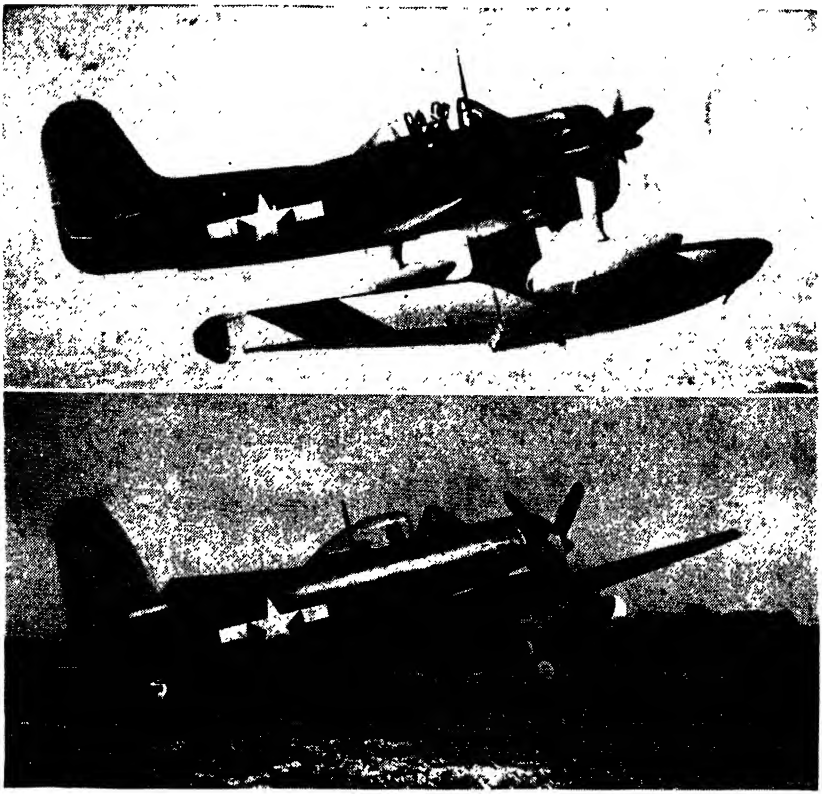


FIG. 189. Scout plane, Seahawk SC2. Top—single-float seaplane. Bottom—land plane with belly tank and radar. (*Airplane Division, Curtiss-Wright Corporation.*)

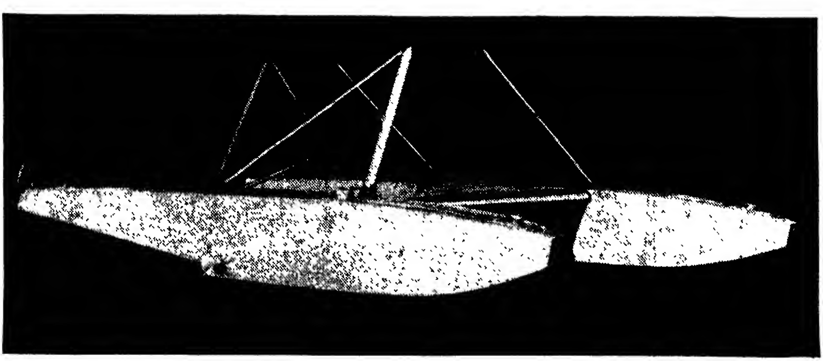


FIG. 190. A pair of twin floats. (*Edo Aircraft Corporation.*)

mal fuselage of the airplane. On small flying boats the power plant must be mounted in nacelles supported above the wing in order to keep the propeller clear of the water. Such an arrangement adds appreciably to the airplane drag and, too often, is inefficient. Larger flying

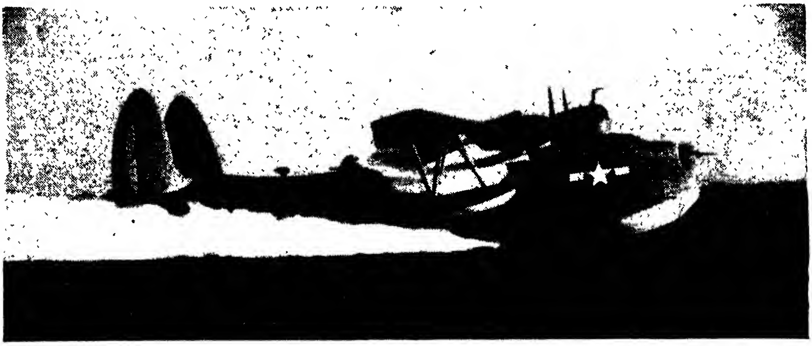


FIG. 191. Flying boat taxiing, PBM-5 Mariner. (*The Glenn L. Martin Company.*)

FIG. 192. The *NC*4 flying boat, the first airplane to cross the Atlantic (1919). (*Bureau of Aeronautics, U.S. Navy.*)

boats are usually high-wing monoplanes, and nacelles may be more efficiently located on the leading edge of the wings. Fin and rudder must be high to clear the heavy spray formed while taxiing or landing (Fig. 191). The hull is never wide enough to keep the boat upright on the water. Wing-tip floats are required. In a few types these are retractable but more often are rigidly fixed to the wing. Another way to pro-

vide the necessary margin against tilting is to fit small stubs, or *sea wings*, on the sides of the main hull. Development of long-range flying boats is illustrated by Figs. 192 to 195. Figure 192 shows the U.S. Navy *NC*4, a biplane with braced wings, tails on outriggers, span, 126

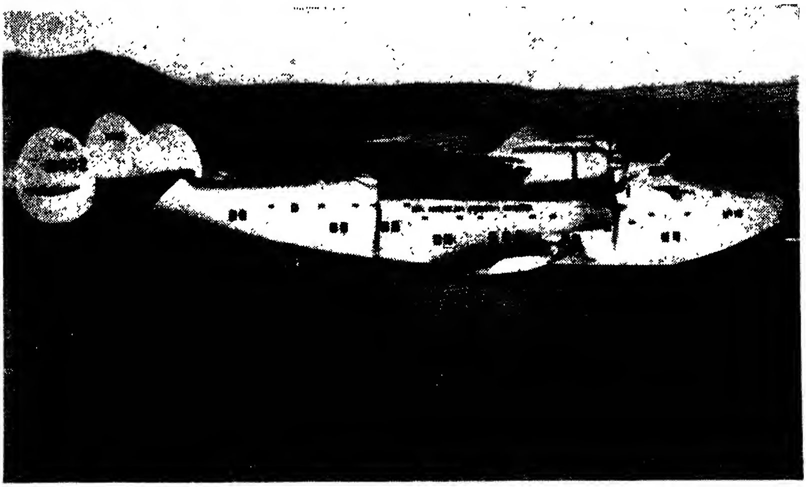


Fig. 193. Flying boat *Atlantic Clipper* 314. First North Atlantic scheduled transport flights, May, 1939. (*Boeing Airplane Company.*)

Fig. 194. Naval air transport JRM Mars. (*The Glenn L. Martin Company.*)

ft, weight, 28,000 lb. Figure 193 shows the commercial Atlantic Clipper, a high-wing monoplane with sea wings, still triple tail but on rear of hull; span, 152 ft, weight, 82,000 lb. Figures 194 and 195 show the Navy transport Mars, having wing-tip floats, single tail, span 200 ft, weight, 165,000 lb. Note that each has four engines, but power varies

from 400 for each engine in the *NC*4 to 1,200 in the Clipper and 3,000 in the Mars.

Size and Shape of Float and Hull. Both the seaplane float and the flying-boat hull must be adapted to the needs of the airplane under three different conditions: (1) rest, or slow motion through the water;

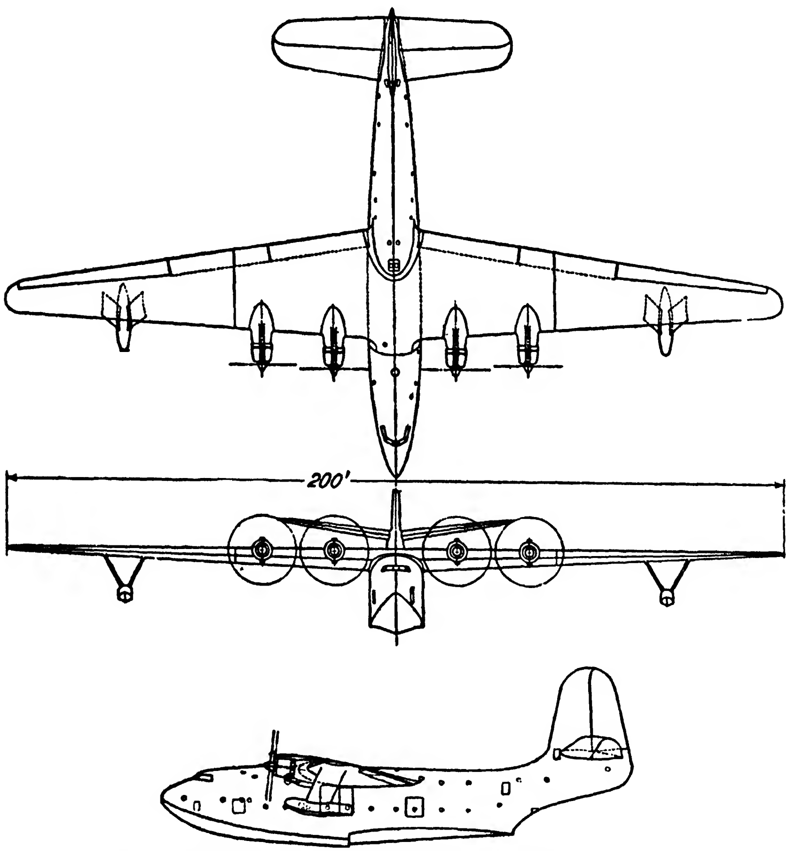


FIG. 195. Three-view sketch of Navy flying boat, JRM Mars. (*The Glenn L. Martin Company.*)

(2) rapid motion on the surface of the water; and (3) flight through the air. The first two conditions obviously demand that the structure be watertight, and the third that the form be one of low air resistance. The second condition calls for small water resistance. The usual requirements of high strength, rigidity, and light weight obviously hold for floats and hulls just as for other airplane parts.

To support a float seaplane with a proper margin of safety when it is at rest on the water, the float must be large enough so that if it were wholly submerged, it would displace a weight of water considerably greater than the total weight of the machine. Under ordinary conditions the float rides with about half its volume out of water. The hull of a flying boat is usually much larger than this in proportion to the weight to be supported.

The float or hull must be long enough to prevent the airplane from pitching so much as to nose over forward or dip its tail into the water. In a float, this necessity of keeping the tail out of the water involves greater length and a larger cross section at the stern than would be adopted if the form were determined solely with a view to minimum air resistance.

The shape of the float or hull is of great importance, since it is only when this is correct that the seaplane is able to get off the water. In Fig. 189 the float is a form widely used in the United States. In side view the top line of the deck is nearly horizontal from stem to stern. The bottom line of the keel curves downward from the bow, at first sharply, and then more gently until near the middle it is substantially parallel to the line of the deck. About six-tenths of the distance back from the bow there is an abrupt break or *step* in the bottom, behind which the keel slopes upward and backward to the stern. In cross section the deck or upper surface of the float is approximately an arc of a circle, and the bottom has the form of a concave V with the keel at the vertex. At the stern is a *water rudder*, very necessary for steering single-engine seaplanes on the water.

The bottom of a flying-boat hull usually has a form much like that of a seaplane float, but the sides rise nearly straight.

Float and Hull Construction. Wooden floats are strong, rigid, and relatively simple to build, but though light when new, the structures soak up water and increase considerably in weight if the plane is moored out very much. The wooden float is relatively easy to damage, even in very minor accidents, and since many parts are alternately wet and dry, it may deteriorate rather rapidly in service.

The disadvantages of wood as a material for floats and hulls have led to its replacement by metal. Metal floats and hulls, except for certain fittings, are almost always made of duralumin. In Fig. 196 are shown three stages in the construction of an all-metal float. The upper view shows the frame being assembled (upside down) in a jig. The *bulkheads* which divide the interior into several watertight compartments are in place, together with the *keel* and the *keelsons*, additional longitu-

Fig. 196. Three stages in the construction of a metal float. (*Edo Aircraft Corporation.*)

dinal members which reinforce the bottom against the shocks of landing. Several of the *stringers* which support the sides and top are also in position. The middle view in the figure shows the bottom plating being riveted to the framework, and in the lower view the remainder of the covering is being fitted. Every joint in the structure has to be made with rivets, since, as previously mentioned, duralumin cannot readily be welded or soldered. To make a watertight joint, a strip of

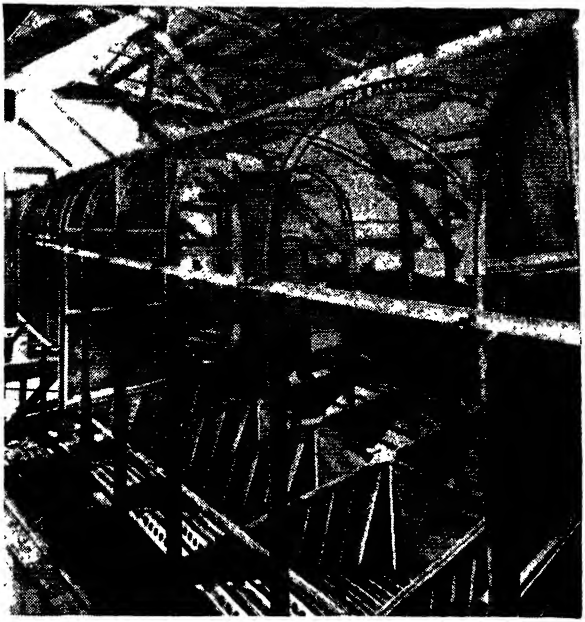


FIG. 197. Framework of S-42 hull. (*Sikorsky Aircraft.*)

canvas soaked in a paint made largely of asphalt is often laid in between the two pieces of metal before the rivets are driven. The asphaltum paint, in addition to making the joint watertight, is very effective in preventing corrosion. The covering of the float is of alclad duralumin sheet, of the same sort as that used for wing and fuselage covering, but thicker. In the top of each compartment of the float is a handhole with a watertight cover which can be easily removed for inspection of the interior, and in the bottom is a drain plug, which can be unscrewed from either inside or outside to let out any water which may have leaked in.

The structure of metal hulls is much like that of floats, though the hull, being larger, requires a more elaborate internal framework. Figure 197 shows bulkheads and widely spaced bottom *frames*, and

beneath them the fore-and-aft stringers, to which the plating is riveted. The bottom plating near the step must be heavy, in order to stand high loads due to the impact of landing in the water.

Seaplane Flight Characteristics. The function of the float or hull is to keep the airplane floating on the water; yet it must offer the minimum possible resistance during take-off. To secure this, a longitudinally flat bottom must be provided. This terminates in a *step*, from which the water flows back cleanly. The step must be located just back of a vertical line through the center of gravity to make the plane trim properly.

After the throttle is opened, the increased thrust moves the plane forward. As the speed increases, the flat bottom acts as a lifting surface. The upward force together with the air lift on the wings lifts the plane until only the very bottom of the float is in the water, thereby eliminating most of the waves usually made by a boat at high speeds and also most of the resistance. The airplane *planes on the step* and accelerates rapidly to take-off. Long stretches of comparatively calm water are needed.

The behavior of a float seaplane in the air is not essentially different from that of a landplane, except that the greater weight and drag of the seaplane float combine to reduce the performance below that of the corresponding airplane with wheels only.

Landing a seaplane or flying boat under favorable conditions is relatively simple, as the pilot merely levels off just over the water and allows the machine to settle in slowly, with the engine idling. The float then planes on the surface of the water and as it loses speed gradually settles deeper until finally the machine comes to a stop. Should the machine descend too rapidly, however, or strike a wave, it may bounce off the water to a considerable height. Such a maneuver is always annoying to passengers, and may even be dangerous, particularly if the airplane has lost flying speed and stalls after bouncing off. A condition of extremely smooth and "glassy" water often offers peculiar difficulties in landing, because of the deceptive impression which it gives the pilot as to his height above it. In really rough water, the difficulty in landing is that the plane may strike the crest of one wave, bound off, and bury itself in the side of the next one, and so be swamped or badly damaged.

Seaplane Uses and Advantages. In spite of the fact that its performance is not as good as that of a corresponding landplane, the seaplane has a distinct field of usefulness. For flights out of gliding distance of land, a seaplane is safer than a landplane, for in good

weather it can remain afloat if forced down, while a landplane usually sinks in a short time. The seaplane does not require prepared airports.

In general, it is less dangerous to fly a seaplane over land than it is to fly a landplane over water. For operations over very rough or heavily wooded country where lakes are numerous, the seaplane is more satisfactory than a landplane. In flying over unmarked territory under conditions of poor visibility, it is frequently possible for a pilot to locate lakes and rivers more easily than landing fields, so that his chances of a successful forced landing are better in a seaplane than in a landplane. A flying boat or even a float seaplane can on occasion make a fair landing on a soft field or long grass.

In large sizes, the flying boat compares more favorably with the landplane, both in weight and speed, than in the small sizes. As the seaworthiness of flying boats improves with increasing size, more arguments favor the use of large flying boats than small. Large boats have proved valuable in patrolling and long-range transport along shores and among islands where airports for large landplanes are nonexistent. Operations may be based on shore stations or special steamships. For transoceanic flying on scheduled routes where adequate airports can be maintained, landplanes have replaced flying boats because of better performance. The additional risk of forced landing at sea is accepted, although rescue of all aboard an old Boeing Clipper flying boat (Fig. 193), following a landing on the stormy North Atlantic near a Coast Guard cutter on weather patrol, demonstrated startlingly that sometimes the flying boat is superior.

The *convertible airplane* is a conventional plane so arranged that a float-type gear may readily be substituted for the landing gear with wheels, should occasion arise (Fig. 189).

Amphibians. An amphibian is essentially a seaplane, usually a flying boat, with wheels which can be lowered into a position below the bottom of the hull when the pilot wishes to alight on land. Figure 198 shows three views of such an airplane, the upper just after take-off from the land, the middle taxiing on the water, and the lower in the air. The wheels swing up and in and fit snugly into recesses in the hull, so that with this arrangement there is no added parasite drag due to the wheel gear.

The performance of an amphibian is not only inferior to that of the corresponding landplane, but also slightly below that of the equivalent seaplane, since the wheel landing gear and its operating mechanism involve additional weight. The great advantages of this type of airplane are, however, evident and make it well suited for services involv-

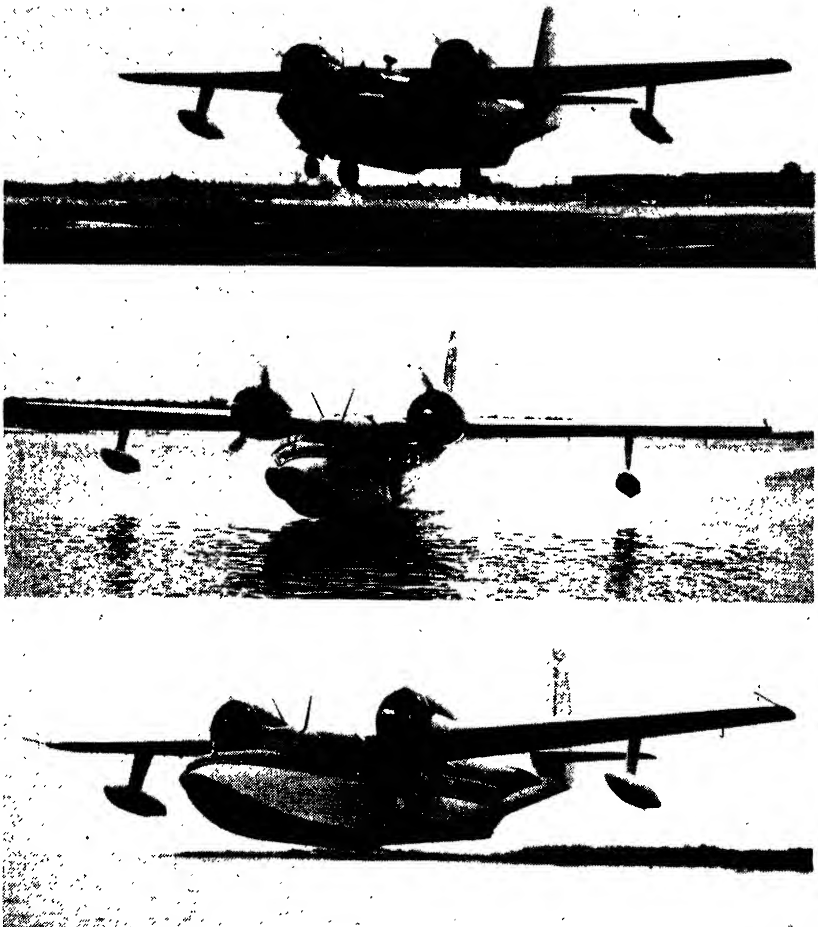


Fig. 198. Mallard amphibian. (*Grumman Aircraft Engineering Corporation.*)

ing flights over wide stretches of land and water. After alighting on the water, the wheels may be put down and the amphibian taxied out onto a sloping *ramp* (Fig. 199), or up a hard shelving beach, thus facilitating the loading of passengers or cargo. Often the landing can be made in a harbor, much nearer the heart of a city than any airport. The amphibian has the advantage of operating from airports when convenient, yet being capable of landing and take-off from water areas feasible for a flying boat of similar size. Summer estates on out-of-

the-way lakes and rivers or islands are brought within comfortable week-end distances for the well-to-do executive.

The plane pictured (Fig. 198), the Mallard, is a rugged capable airplane that, if need should arise, will take off and fly with only one engine operating. It has tricycle landing gear; in Fig. 199 are seen the

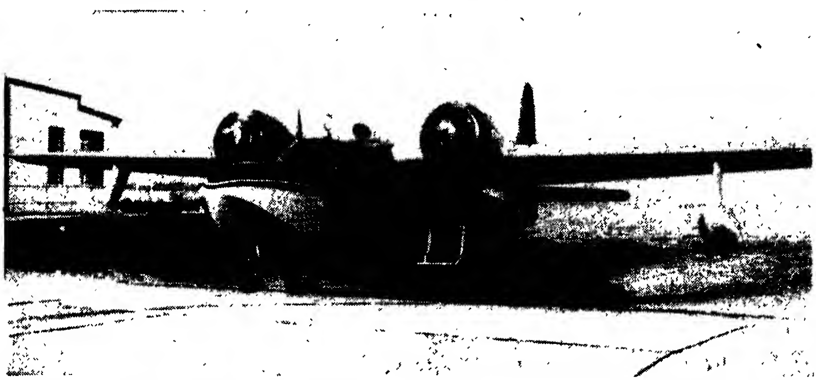


FIG. 199. Mallard climbing out of water. *(Grumman Aircraft Engineering Corporation.)*

doors that close the nose-wheel opening when the wheel is retracted and also some details of struts for retracting the main wheels. The roomy cabin, fitted for six to ten people, is comfortably upholstered, air-conditioned, and soundproofed. The plane has 66-ft 8-in. span, 444-sq ft wing area, and a total weight of 12,500 lb; load of fuel and passengers is 3,000 lb. Two Pratt & Whitney Wasp engines of 600 bhp each make a cruising speed of 180 mph practical. A trip of 1,000 miles may be made without stopping.

CHAPTER XV

THE COMMERCIAL AIRPLANE

The designation *commercial* is applied not only to those airplanes which are used to produce income but also to those which are operated by their owners for pleasure or for business purposes. A commercial airplane, therefore, is one so designed and built that it can render a desirable service at a price that the public or a private owner is willing to pay.

Uses of the Commercial Airplane. Activities of commercial airplanes may be divided into three groups: *air transport, aerial service,* and *private operation.* These groups are not distinctly separated. By air transport is meant the carrying of passengers, mail, or goods over definite routes at scheduled times.

Aerial services include training of pilots, "joy riding," *i.e.*, carrying passengers on short flights around an airport, making of photographs to show some desired object, and mapping, which consists of making a series of overlapping pictures of a territory and assembling them into a flat mosaic or map. The chartering of planes for special flights with passengers or goods, for towing signs, or for skywriting are also aerial services.

Private operation includes flying near an airport for practice, sport, or pleasure, or flying across country, say, to call on a friend, or to go swimming in Florida when New York is frozen in January. Business planes used by one firm to transport executives and salesmen are usually classed as private planes. Private planes owned by individuals or firms may be flown by professional pilots just as most large yachts have professional crews.

Characteristics of the Commercial Airplane. For such a wide variety of duties, planes of all types are required, but they have some common characteristics. They must be safe, reliable, comfortable, and not too expensive to buy and operate.

Safety includes not only the question of the physical integrity of the airplane and its parts but the question of its flying qualities under adverse circumstances. The most troublesome factor is the provision of easy control at low flying speeds; this is particularly needed if the plane is to be landed on other than good fields. Present airplanes are

too dependent on the skill and judgement of the pilot under those conditions.

Reliability of operation as far as the airplane is concerned is largely a question of effective care of the plane on the ground. An old plane excellently maintained is far more reliable than a new one in charge of a careless ground crew. One reason for the superior reliability of transport planes as compared with the average aerial service or private plane is the better maintenance.

Reliability is also affected by external circumstances. Fog and ice are still handicaps to flying. Improvements in radio beacons have made flight through fog and snow possible for planes with adequate equipment and well-trained pilots. Landings of regular flights with ceiling of clouds below about 200 ft above the runway and visibility less than about ½ mile are not permitted even on airports with instrument landing paths and *approach radar* systems. (The half mile is covered in about 15 sec at approach air speeds.) If conditions at the destination are poorer than these minimums of ceiling and visibility, the airplane must seek an alternate airport. Experimental and emergency landings have been made with ceiling and visibility zero-zero. With snow there is the added difficulty of drifting on runways, effectively closing the airport until it can be cleared. If of even depth, it might stop the plane so quickly that damage would result; even more hazardous are irregular drifts that slow one side of the plane, causing an uncontrollable skid or *ground loop* and possible disaster. Drifted snow will also cause serious damage to propellers. Ice, formed by the freezing on the airplane of water droplets suspended in the air, is a menace to cloud flying in the winter months. Nothing can prevent the formation of the ice; it can be dislodged by mechanical de-icers, or melted by heat before the added weight or change in aerodynamic properties becomes serious. Ice may form in carburetors; this is avoided by heating the intake air.

Comfort is a combination of space, freedom from air blast and noise, temperature, and ventilation. These factors can hardly be controlled in open-cockpit airplanes; the result, exactly the same that occurred in automobiles, is that almost all airplanes have closed cabins. Space in an airplane cabin must be limited to keep parasite drag low. Noise is avoided by insulating the cabin walls and decorating them with soft materials. Ventilation with air of moderate temperature must be provided in such a way that noise is not admitted. Such things as opening of windows or direct air vents through the walls cannot be permitted. Temperature must be controlled by cooling as well as heating the

incoming air, particularly in cabins with pressure maintained well above that of the outside air. The air conditioning of large transport planes is much more satisfactory than can be achieved in small planes. Stopping the noise at its source by muffling the engines and by reducing the propeller noise by lowering the tip speed has been attempted only for small planes.

Airplanes have been built in comparatively small numbers and hence have been expensive. Consideration of operating cost must include a large item for depreciation. This can be reduced only by lowered first costs, longer life, or more intensive usage. A plane flown only on week ends is a costly luxury.

Other items which are excessive as compared with other vehicles are the costs of gasoline and oil, maintenance, hangar space, and insurance. A reduction in consumption of gasoline and oil has double benefit; it not only results in a direct saving in cost but also permits carrying a greater pay load.

Air Transport Planes. For main-line domestic routes, United States air transport companies use only one general type of airplane: a low-wing cantilever monoplane, with conventional fuselage and tails, wheels retractable (all new ones have tricycle landing gear), two or four engines in leading-edge nacelles, capacity from 14 to 60 passengers. Newly designed four-engine planes have cabins pressurized for passenger comfort and to permit flight at higher altitudes. This feature was first introduced in air-line operation in the Boeing 307 Stratoliner.

Routes are usually competitive; hence there is rivalry to establish high block-to-block speeds and short-time schedules, particularly on longer flights. Nonstop or one-stop flights for long routes are usually quicker and more attractive to passengers, even though, through lowering of per cent of passenger seats occupied or carriage of excessive fuel loads, operating expenses are higher. One-stop flights from New York to Los Angeles are scheduled at about 220 mph including a 25-min stop.

Safety requirements include ability to complete a take-off, once started, even if one engine fails, and to fly with one engine stopped. Single-engine planes are not tolerated even for minor or feeder-line routes. Four-engine planes on long routes, along which more than an hour and a half's flight would be needed to reach an emergency airport, must be able to fly on two engines.

For transoceanic routes the same types of four-engine airplanes are used, and schedules are planned for air speeds only slightly lower than those on domestic routes. When one air line has a monopoly on a cer-

tain route with steamships as its only rival, slower and more economical speeds may be used, but with rival air lines of several nationalities competing for the travelers who need to reach Europe quickly rather than luxuriously, cruising at highest engine cruising output is more usual. Slower speeds permit savings in fuel per mile, lowering costs and allowing more pay load. Roughly air-line costs are divided somewhat like this: for fuel and oil, 9 per cent; for flight crews, 12 per cent; for ground personnel (mechanics, engineers, ticket salesmen, also executives, secretaries, etc.), 40 per cent; replacement and depreciation, 15 per cent; insurance and taxes, 7 per cent; miscellaneous, 17 per cent. Thus a saving of a few per cent of the fuel costs is a small part of the total and might be offset by revenue loss if schedules were less convenient owing to lower speed operation. For one domestic air line in 1947, passenger revenue was 85 per cent of the total, mail only 6 per cent, and cargo 7 per cent.

Aerial Service Planes. Planes to fulfill the many tasks called "aerial service" vary with the type of service. For training of civilian students, small low-powered two-seaters are used. Cruising speed need not be high; good take-off and reasonably easy landing characteristics are essential. High-wing braced monoplanes with fixed landing gears are the usual type.

For flying of passengers around airports, "joy riding," to enable them to see their city or their houses, speed is still relatively unimportant. Often cabin planes similar to the trainers but seating three or four people are used. For short charter flights, planes of the same size but of higher cruising speeds are usual; presently popular are trim little cantilever monoplanes with retractable landing gears. Since the end of the Second World War, there have been no medium-size single-engine planes. For longer charter flights or for larger parties, twin-engine planes have replaced the single-engine ones. Many of these are converted from small military transports.

Aerial photographs may be conveniently taken from many of the charter planes. For mapping, planes capable of flying smoothly at fairly high altitudes are required. Mapping cameras make exposures automatically as the pilot flies over a strip of territory; he then flies back, photographing an adjacent strip, etc. The prints are fitted carefully together like a mosaic and a true picture of all features of the ground obtained.

Planes for Private Operation. For private operation, planes fall into two groups: first, those for use on trips about the country for pleasure or business, and, second, those for use in practice or short flights.

Those of the first group are the same types as the charter or smaller transport planes, but are specially fitted for individual use. Operating costs are high, and skilled pilots, often professional, are required.

In the second group, the majority of the planes are light, braced monoplanes, the same types used by aerial service companies for training and "joy riding." Considerable skill is needed to learn to fly one, and also much practice to retain the skill once acquired.

Several types of planes arranged for simple flying have been made. Of these only one, a development of the original Weick "easy-to-fly" plane built by Engineering & Research Corporation, the Ercoupe, has been widely sold. Most of the others failed to combine easy flying qualities and improved safety with fair cruising speed and range. The Ercoupe has only two flight controls: ailerons and elevator (there is a rudder on each twin fin, but even as on the first planes of the Wright brothers, they are moved only by connection to the ailerons), tricycle landing gear, steerable nose wheel for ease in taxiing. In addition, it cannot be spun, either deliberately or accidentally, an important safety feature.

Another handicap of the private airplane is that the excessive noise at take-off hinders seriously the establishment of small fields or airstrips close to residential communities. The two sources of excessive noise are the unmuffled engine and the propeller, which, even on the smallest planes, turns at high tip speed, especially at full take-off rpm. On airplanes mufflers have never been much used because noises are peculiar things that do not add together directly, but logarithmically, and if a loud noise comes from two sources, as in the airplane, complete elimination of one source leaves 90 per cent of the noise. The reduction of propeller noise can be made only by reducing radically the tip speed. A secondary gain can be obtained by using many blades instead of two. Pioneer work to determine the benefits of these changes in the propeller was done by the NACA. Figure 200 shows the experimental "quiet airplane." Engine must be geared to reduce the rpm, blades added, possibly even very wide blades used to quiet the "rustle" of slow-moving ones if the section lift coefficients are too high. Once the propeller is quieted, the engine must be carefully muffled to remove the other large noise source. Commercial silencers can be used, although the NACA plane has a special muffler. Both demonstration and noise-measurement tests of the NACA plane proved that a radical reduction in noise is possible. Engine and propeller are both more expensive than those normally used on light airplanes. The purchaser must pay the difference, but will do so only if the plane can give better service.

In this case "better service" would be permission to operate from airstrips located close to residential areas. Legislation was finally required to enforce use of mufflers on automobiles and motorboats; possibly similar laws may be passed with regard to all airplanes, not only

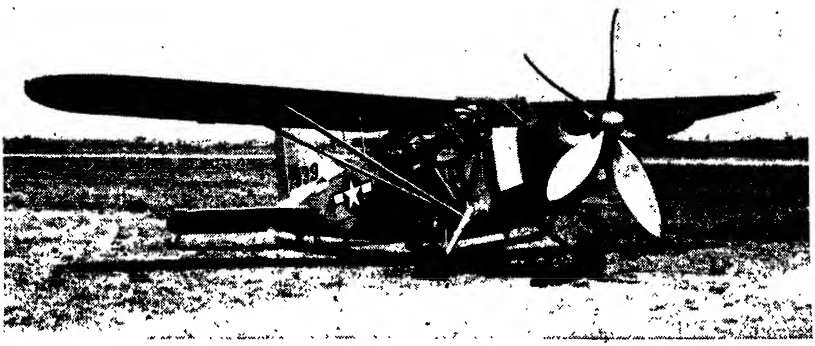


FIG. 200. NACA quiet airplane. (*National Advisory Committee for Aeronautics.*)

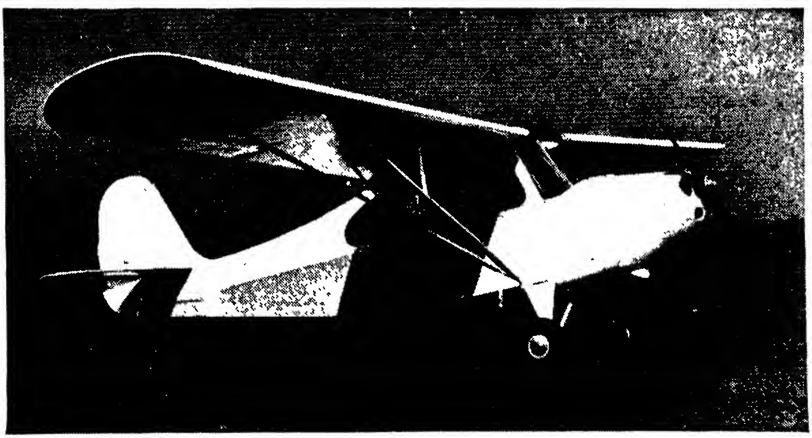


FIG. 201. A typical light airplane, Champion. (*Aeronca Aircraft Corporation.*)

small ones, not specifically laws that mufflers must be used, but against *noise.*

Typical Commercial Airplanes. Following are brief descriptions of typical airplanes for several different civilian uses. Some dimensions are tabulated at the end of this chapter.

Aeronca Champion (Fig. 201). A light, braced monoplane seating pilot and passenger in tandem, this airplane is much used for training. Cabin is closed, but with large windows. Wing is fabric covered over

spruce spars and stamped dural ribs. Wing loading is very low; hence no flaps are fitted. Wheels have mechanical brakes. Engine is 65 hp, Continental four-cylinder opposed type.

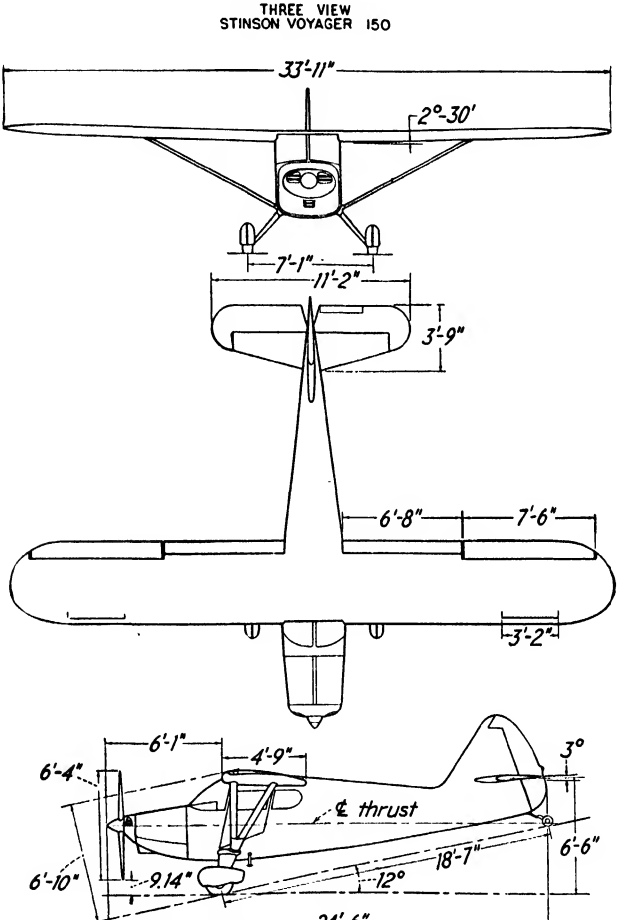


FIG. 202. Three-view sketch of Voyager. (*Stinson Division, Consolidated Vultee Aircraft Corporation.*)

Stinson Voyager.[1] Larger, faster, more suitable for business and pleasure flying between cities, the Voyager seats four, pilot and three passengers, comfortably in a well-upholstered, sound-insulated, and heated cabin. A three-view sketch is shown in Fig. 202. On a later model a tab is fitted on the rudder as well as on the elevator. These

[1] Built by Piper Aircraft Corp. in 1949.

control tabs can be adjusted by the pilot to reduce control forces while cruising. The engine, shown installed in Fig. 203, is a six-cylinder opposed Franklin giving 165 hp, fitted with an electric starter. Propeller shown is fixed-pitch, but a controllable propeller may also be fitted. Cruising speed is 130 mph at 5,000 ft altitude. Two tanks, each holding 25 gal, provide fuel for a range of about 500 miles. Take-off is short, about 500 ft with full load. The wing has metal spars and ribs with fabric cover. Fuselage is welded steel tubing with fabric cover.

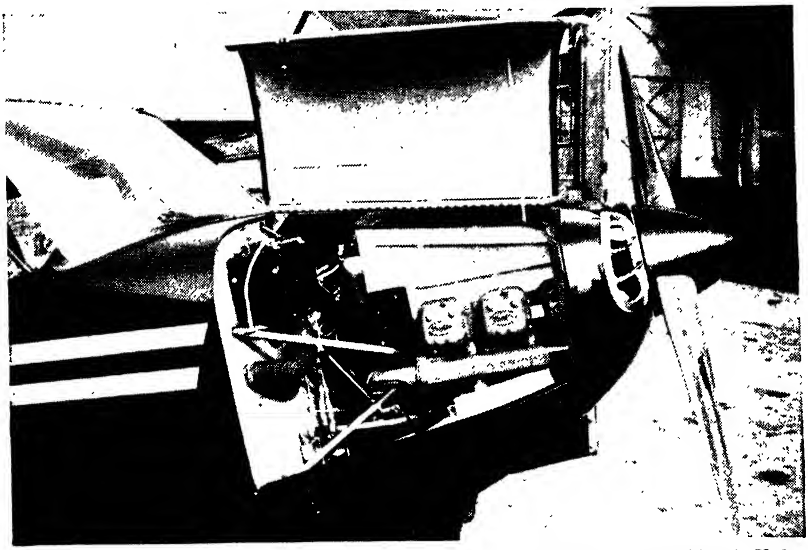


FIG. 203. Engine installed in Voyager. (*Stinson Division, Consolidated Vultee Aircraft Corporation.*)

Flaps are fitted to provide improved take-off and landing speed. They are mechanically operated by a lever at the pilot's right hand. Wings have slots near tips to improve low-speed control. Main wheels have hydraulic brakes operated by tilting the rudder pedals. Brakes may be locked for parking. Tail wheel is steerable and swiveling.

Figure 204 shows the dual wheel controls (push-pull for elevator control, turn for aileron control) and an instrument installation providing minimum requirements for blind flying. Starting at the top is the *magnetic compass*, in next row left to right: *air-speed meter*, *sensitive altimeter*, *ball-bank* and gyroscopic *turn meter*, *rate-of-climb meter*, *tachometer;* next, on level with control wheels: extreme left, *radio*, next *oil-pressure gage*, *oil-temperature indicator*, *clock*, *fuel gage*, *ammeter;* bottom row grouped in center are engine controls: main *throttle* pulled

back for *closed*, pushed forward for *open*, with *carburetor heat control* and *fuel-tank selector valve* at left, *ignition* and *starter switch* and *mixture control* at right. At far left are *parking-brake knob*, three *light switches;* at extreme right, *cabin heat control.* Adjusting cranks for elevator and rudder tabs are overhead (out of the picture).

Other planes for four passengers include the Beech Bonanza and Ryan Navion. These are less simple and more expensive, with higher

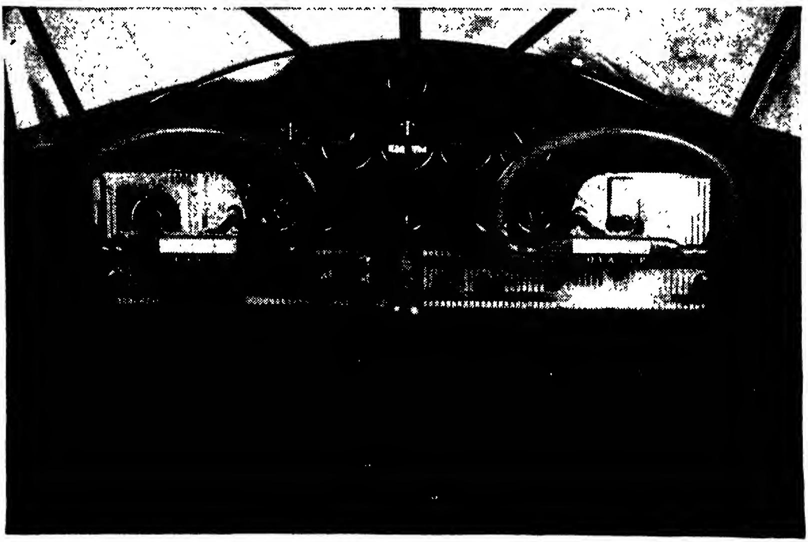


FIG. 204. Instrument panel of Voyager. (*Stinson Division, Consolidated Vultee Aircraft Corporation.*)

cruising speeds. Both are low-wing monoplanes with retractable, tricycle landing gears.

Beech D18. One of the few small twin-engine planes currently being built, the D18 is used as an executive, charter, or small transport plane. It is a low-wing monoplane, with retractable main wheels and twin vertical tails. The usual arrangement is for pilot, copilot, and six or eight passengers. Either Wasp Jr. or Continental engines are fitted. Cruising speed is about 210 mph.

Martin 2-0-2 (Figs. 205 and 206). This plane is a postwar twin-engine transport capable of fulfilling all the requirements for new transport aircraft, and at the same time offering economical operation and increased cruising speeds for attractive schedules. The plane is an all-metal low-wing monoplane with tricycle landing gear. Engines are Pratt & Whitney Double Wasp 2800's rated at 1,800 bhp each at 6,500

ft altitude, permitting comfortable cruising at 10,000 ft at 270 mph. For some routes high-blower engines yielding 1,600 bhp up to 16,000 ft are used. Propellers are three-blade Hamilton Standard, automatic-feathering and reversing. Front wheel is steerable to facilitate taxiing.

Passenger comfort is increased by a wide aisle and deeply upholstered adjustable chairs. Normal seating is for 40 passengers in four rows. The cabin is well air-conditioned and soundproofed. Passengers enter and leave by folding stairs hydraulically operated from inside the plane.

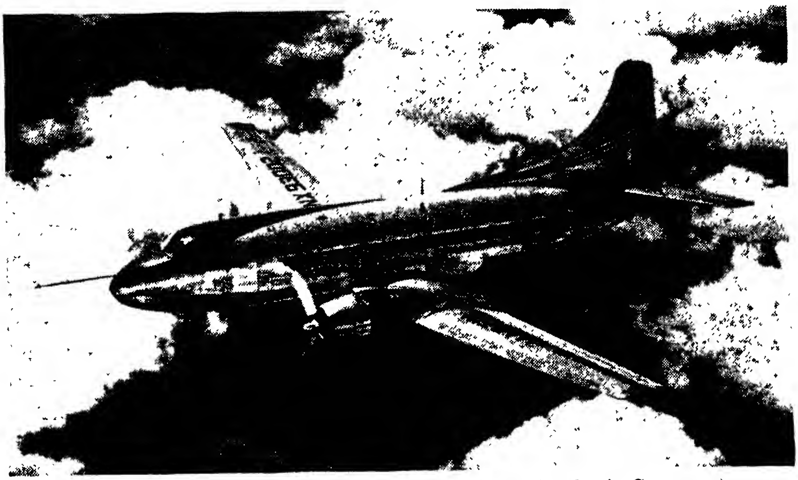


FIG. 205. Martin 2-0-2 transport. (*The Glenn L. Martin Company.*)

Fuel cells in the wings may be filled by pressure lines to the underside of the wing; this shortens the refueling time. Throughout the plane provisions have been made for easy maintenance. Wing leading edges are heated by separate combustion heaters to provide de-icing. Propeller blades are de-iced electrically.

Consolidated-Vultee 240. Another twin-engine low-wing monoplane with tricycle gear, this new plane also carries 40 passengers. Engines are also Pratt & Whitney 2800's with Hamilton Standard three-blade feathering and reversing propellers. Thermal de-icing from exhaust heat is provided.

Cabin is well ventilated with complete change of air in 3 min, heated, cooled, dried, or humidified as need be. Cabin is pressurized for better comfort at high altitudes and during changes in altitude.

In Fig. 207 it can be seen that there are no cowl flaps or gill openings. The exhaust is used as an ejector to draw the cooling air past the engine fins. Exhaust and cooling air leave the cowl through nozzle forming a

jet that assists in propelling the plane. With this aid the plane will cruise at about 300 mph at 16,000 ft.

Double-wheeled tricycle landing gear shows clearly in Fig. 208.

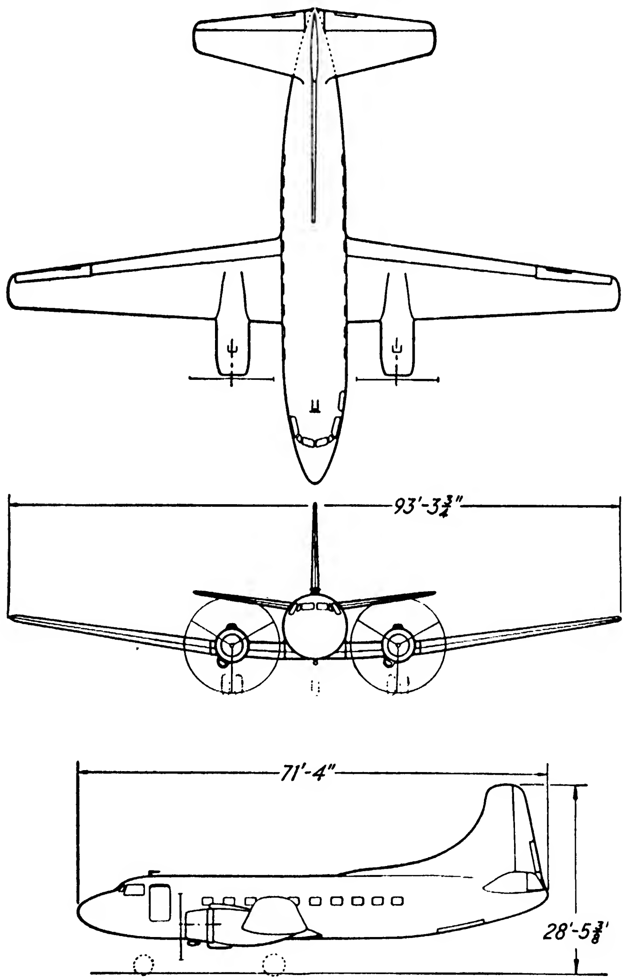


FIG. 206. Three-view sketch of Martin 2-0-2. (*The Glenn L. Martin Company.*)

Douglas DC-4 *or* C-54 (Fig. 209). Most of the four-engine transports were in 1948 converted Army Air Transport Command C-54's from the Second World War. These were fitted with Pratt & Whitney 2,000 engines of 1,100 bhp each at 8,500 ft and Hamilton Standard Hydromatic propellers. With tricycle landing gear, they provide com-

be replaced by upper and lower berths. Cabin is pressurized and well air-conditioned.

The four engines are Pratt & Whitney 2800's rated at 1,800 bhp each, but producing 2,100 bhp at take-off. Propellers are Curtiss Electric or Hamilton Standard, feathering and reversible, 13 ft 1 in. in diameter. Landing gear is tricycle, fully retractable with dual main wheels and steerable nose wheel. Wings and tail are de-iced by hot air in ducts along the leading edges. Propellers have electric de-icing. Wing has

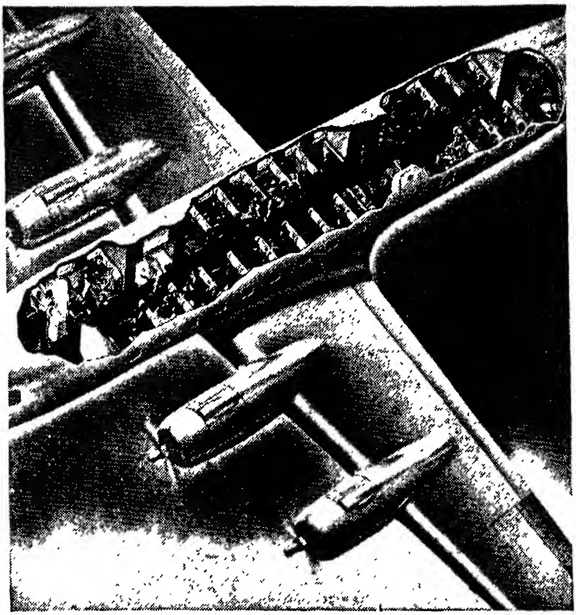


FIG. 211. Interior of DC-6. (*Douglas Aircraft Co., Inc.*)

double-slotted flaps to reduce the landing speed. Skin of wing and fuselage is largely the stronger alloy 75S, saving about 800 lb in weight of structure.

Flight tests show some interesting performance figures. At 84,000 lb weight, the highest cruising speed using 1,175 bhp per engine is 315 mph at 20,000 ft; at the same height the maximum rate of climb is 650 ft per min. Ceiling with four engines is 27,000 ft; with three engines, 21,000 ft. Take-off safe runway length, with allowance for improbable engine failure, is 5,500 ft. Safe landing at 75,000 lb weight requires a 4,900-ft runway. Maximum range with 3,300 gal of fuel is 3,500 miles.

Lockheed Constellation. This airplane is also a deluxe four-engine air liner with pressure cabin. In flight it may be readily recognized by its

drooped nose and triple vertical tail (Fig. 212). It is widely used for long-distance and transoceanic operation by civil air lines of many countries.

There are many cabin arrangements, varying from 64 deluxe day seats to 34 berths for ocean trips. Similarly, fuel loads are varied to suit the trip, with a maximum of 5,700 gal providing for over 5,000-mile range, permitting New York-to-London flights without stop. For shorter trips, a canoelike cargo container called a "Speedpak" may be loaded at leisure, then attached to the bottom of the plane for flight to

FIG. 212. Constellation. (*Lockheed Aircraft Corporation.*)

its destination; this is seen beneath the fuselage in Fig. 212. It holds 8,000 lb of cargo. When attached to the plane, it, like all other cargo compartments, is fitted with fire-detecting and -extinguishing systems.

The power plant has four Wright, 18-cylinder, duplex Cyclone engines each giving 2,500 bhp for take-off, 2,100 bhp at 4,400 ft, and 1,800 bhp at 16,000 ft. Propellers are Curtiss Electric or Hamilton Standard, 15 ft 1 in. in diameter, feathering and reversible. Maximum cruising speed is over 325 mph.

The tricycle landing gear has dual wheels for both main and nose wheels. Flaps are of the Fowler type. De-icing boots of the air-pulsating type are fitted to leading edges of wings, stabilizer, and fins. To make control operation easier, power boosts are used that automati-

TABLE 12. CHARACTERISTICS OF TYPICAL COMMERCIAL AIRPLANES

Characteristic	Aeronca Champion	Stinson Voyager	Ryan Navion	Beech D18	Grumman Mallard	Martin 2-0-2	Convair 240	Douglas DC-4	Douglas DC-6	Lockheed Constellation	Boeing Stratocruiser
Weight, lb	1,220	2,400	2,750	8,750	12,750	38,000	39,500	73,000	93,200	102,000	135,000
Span, ft	35.2	34.0	33.4	47.6	66.7	93.3	91.8	117.5	117.5	123.0	141.3
Wing area, sq ft	170	155	185	349	444	864	817	1,457	1,457	1,650	1,720
Length, ft	21.5	25.2	27.3	33.9	48.3	71.3	74.7	93.4	100.6	95.1	110.3
Weight empty, lb	750	1,300	1,680	5,640	9,200	25,800	25,500	40,400	52,100	61,500	77,700
Fuel, gal	13	50	40	200	380	1,030	1,000	3,590	4,240	5,700	7,700
Engines	1 Cont.	1 Frank.	1 Cont.	2 P & W	2 P & W	2 P & W	2 P & W	4 P & W	4 P & W	4 Wright	4 P & W
Take-off power, bhp	65	165	185	900	1,200	4,200	4,200	5,800	8,400	10,000	14,000
Cruising speed, mph	90	130	150	212	180	270	300	230	310	328	320
At altitude, ft	0	5,000	5,000	10,000	8,000	10,000	16,000	15,000	20,000	23,000	25,000
Weight per square foot, lb	7.2	15.5	14.8	25.0	28.7	44.0	48.4	50.2	64.0	61.8	78.5
Weight per brake horsepower, lb	18.8	14.5	14.8	9.7	10.6	9.1	9.4	12.6	11.1	10.2	9.8

cally multiply the pilot's efforts. Further relief for pilot and copilot is provided by a flight engineer, who handles details of operation and cruise control. On long flights, a combined navigator and radioman is usually included in the crew. There may also be a spare pilot.

Boeing Stratocruiser (Fig. 33). Flying but not yet (1948) in air-line service is this much larger four-engine plane. It was planned for use on long flights, though for short trips it can carry 100 passengers. Passengers will enjoy two decks with lounges and cocktail bar on the lower deck. Pressurization of the cabin will maintain sea-level pressure in the cabin up to about 15,000 ft, and even at 30,000 ft the cabin pressure will be that of only 8,000 ft. High cruising speed will be about 350 mph.

Landing gear is dual-wheel tricycle type, with the low retracting time of 9 sec. Flaps are Fowler type. The plane has the characteristically high and large Boeing vertical tail. Rudder has hydraulic boost control. Thermal de-icing is used on wing, stabilizer, and fin. Minimum flight crew consists of pilot, copilot, and flight engineer.

The engines are Pratt & Whitney Wasp Majors rated at 2,800 bhp each and permitting 3,500 bhp each for take-off. The engines have exhaust-turbine-driven superchargers to maintain rated power well above 20,000 ft. Propellers are Curtiss Electric, 16 ft 8 in. in diameter, feathering and reversible.

Dimensions of typical commercial airplanes are given in Table 12.

CHAPTER XVI

MILITARY AIRPLANES

In the Second World War, the influence of air power became enormous. Cooperating with land and sea forces during advances and landings, tactical air forces had two difficult tasks: first, to obtain and maintain air superiority; second, to attack and destroy enemy installations, ships, and communications. Scouting forces searched far and wide over enemy territory, photographing new activities and locating troop movements, or over the ocean and among islands to discover enemy ships. Strategic air forces bombed enemy territory independently, effectively crippling the military installations and industrial might of the enemy, hence his power to make war. Many types of planes were needed for these purposes, most based on land, some on aircraft carriers, a few on the sea.

For defensive missions in the tactical use of airplanes, the principal types of airplanes are single-seaters of the highest possible speed, climb, and maneuverability, variously called *pursuit planes*, *fighters*, and *interceptors*. These are armed with fixed guns, ordinarily in the wings. On some, six or eight 50-caliber machine guns were fitted; others carried fewer 20-mm cannon. Such guns are aimed by pointing the plane at the target. For defense against disturbances at night, pursuit groups were directed by radar from ground or ship. There were also some larger night fighters with crews of two or three, carrying their own radar that in some cases directed guns. In these larger fighters as well as in bombers, some guns were flexibly mounted, aimed directly by a gunner, or in a turret controlled by a gunner inside, or on the later bombers and in night fighters, in turrets remotely controlled from a central sighting position.

For offensive tactical missions, fighter planes were also used to strafe ground targets with guns and sometimes with medium-sized bombs, dropped usually from dives. Next in size come dive bombers, torpedo bombers, and attack planes, some carrying many fixed guns or cannon (35 mm or even 75 mm) as well as bombs. All these fighters and bombers also carried rockets. Medium bombers were sometimes part of the tactical air force; at other times they carried out strategic missions.

In the search forces, photographic planes for short ranges were usually specially modified unarmed pursuit planes; for longer ranges fast medium or attack bombers were also modified for photographic missions. From carriers, search missions were made by fighters and dive bombers. Used also for naval search flights were long-range patrol bombers, either landplanes or flying boats.

Strategic bombing was done by long-range large bombers—all four-engine landplanes. For daylight missions, these were escorted by long-range pursuit planes. For defense, the bombers bristled with machine guns. A few strikes deep into enemy territory by Navy task forces spearheaded by carrier-based dive bombers might also be considered strategic.

There follow pictures of some of the types of United States planes that contributed to success in battle in the Second World War. To these planes and to all the planes of the Army and Navy air forces and their daring crews we owe a debt.

ARMY AIR FORCE PLANES

Figure 213 shows the three most used Army Air Forces fighters: the P-38 Lightning, the P-47 Thunderbolt, and the P-51 Mustang. Guns show in the wings of the single-engined Thunderbolt and Mustang and in the nose of the Lightning. Lightning and Thunderbolt have turbo-supercharged engines. On the Lightning are seen external gasoline tanks that extend the range of the fighter to permit escort of long-range bombers.

On Fig. 214 are shown two medium bombers: the B-25 Mitchell and the B-26 Marauder. Guns for strafing, as well as for defense, are seen in the nose, on the fuselage side just ahead of the wing, in the waist, and in the tail. Bombs are carried internally in the fuselage bomb bay and released by the bombardier sighting through the sloping flat window on the nose. It was in 16 B-25's under Lieutenant Colonel (later General) Doolittle that the first air raid on Tokyo was made on Apr. 18, 1942. Take-off was from the aircraft carrier *Hornet*.

Three long-range heavy bombers of the Army Air Forces are pictured in Fig. 215: the B-17 Flying Fortress, designed by Boeing, built also by Douglas and Lockheed; the B-24 Liberator, designed by Consolidated Vultee, built also by the Ford Motor Company; and the B-29 Superfortress, designed by Boeing, built also by Martin and Bell. Many turrets are seen on the B-17 and B-24; these were power-operated with a gunner in each turret. The smaller rounded turrets on the B-29 are controlled from a single sighting station. The B-29 cabin and the tail-

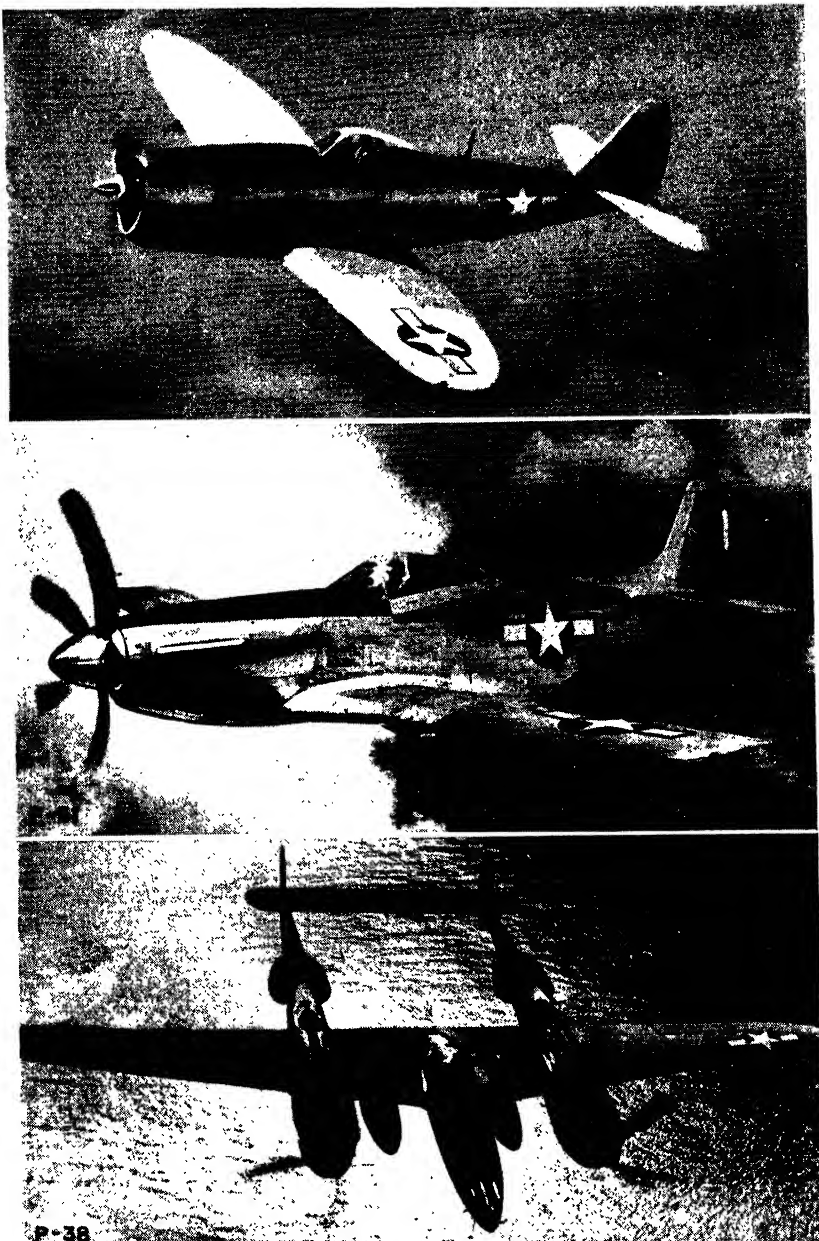


FIG. 213. Pursuit planes P-47, P-51, P-38. (*U.S. Army A.A.F. and Republic Aviation Corporation.*)

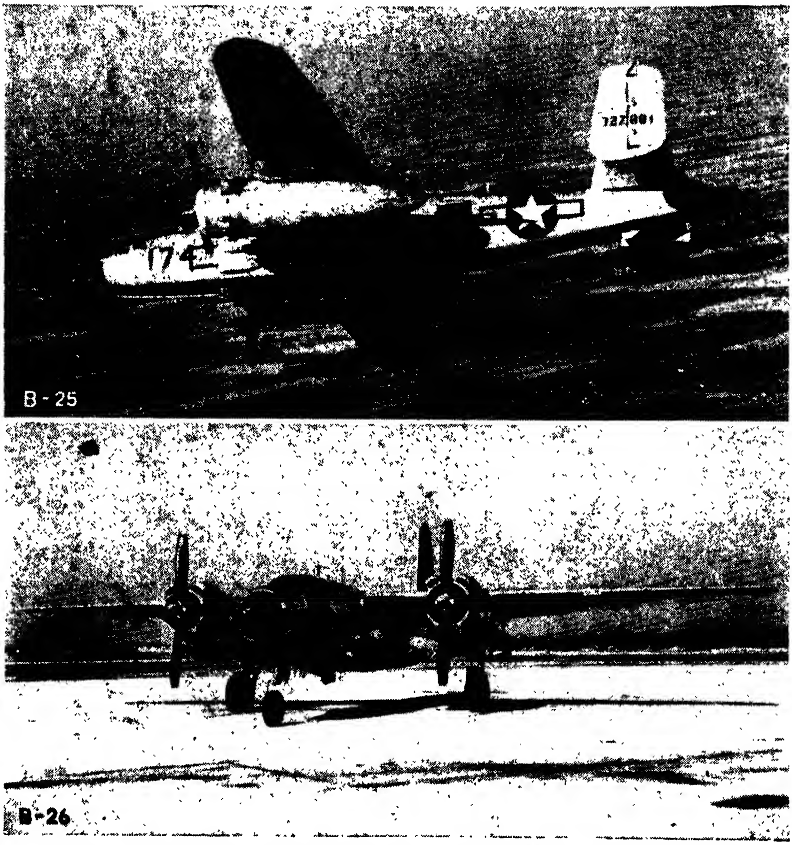


FIG. 214. Medium bombers B-25, B-26. (*U.S. Army A.A.F. photographs.*)

gunner's station are pressurized to increase the effectiveness of the crew on long missions at high altitude.

NAVY PLANES

Carrier-based fighters of the U.S. Navy are shown in Fig. 216: F4F, the Grumman Wildcat that held the line against superior odds in the early days at sea and even on land at Guadalcanal; F6F, the Grumman Hellcat, its much improved successor; and F4U, the Vought Corsair. Though fighters, the Hellcat and Corsair were also rocket carriers and bombers, attacking not only ships but heavily defended shore installations.

Figure 217 is the carrier-based dive bomber SBD, Douglas Dauntless, shown just after bomb release with perforated dive flaps or brakes

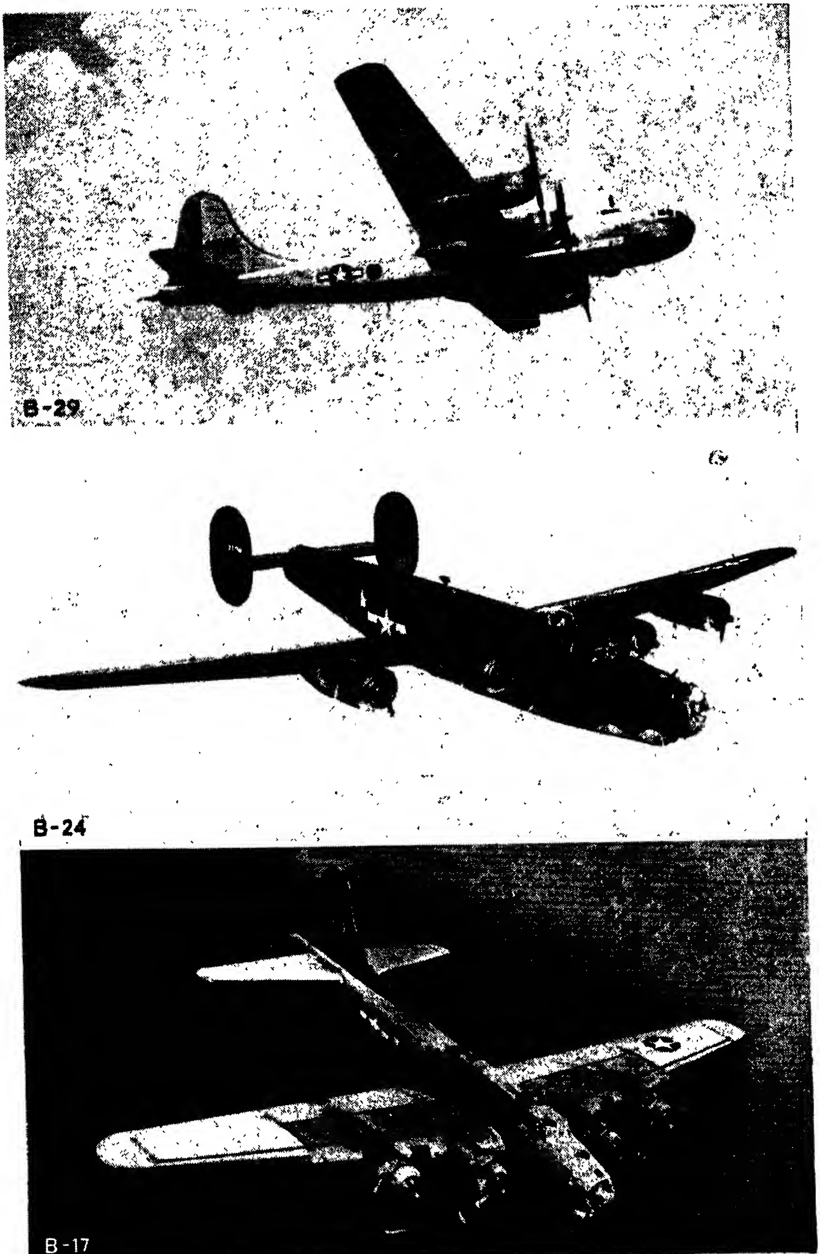


FIG. 215. Strategic bombers B-29, B-24, B-17. (*U.S. Army A.A.F. photographs.*)

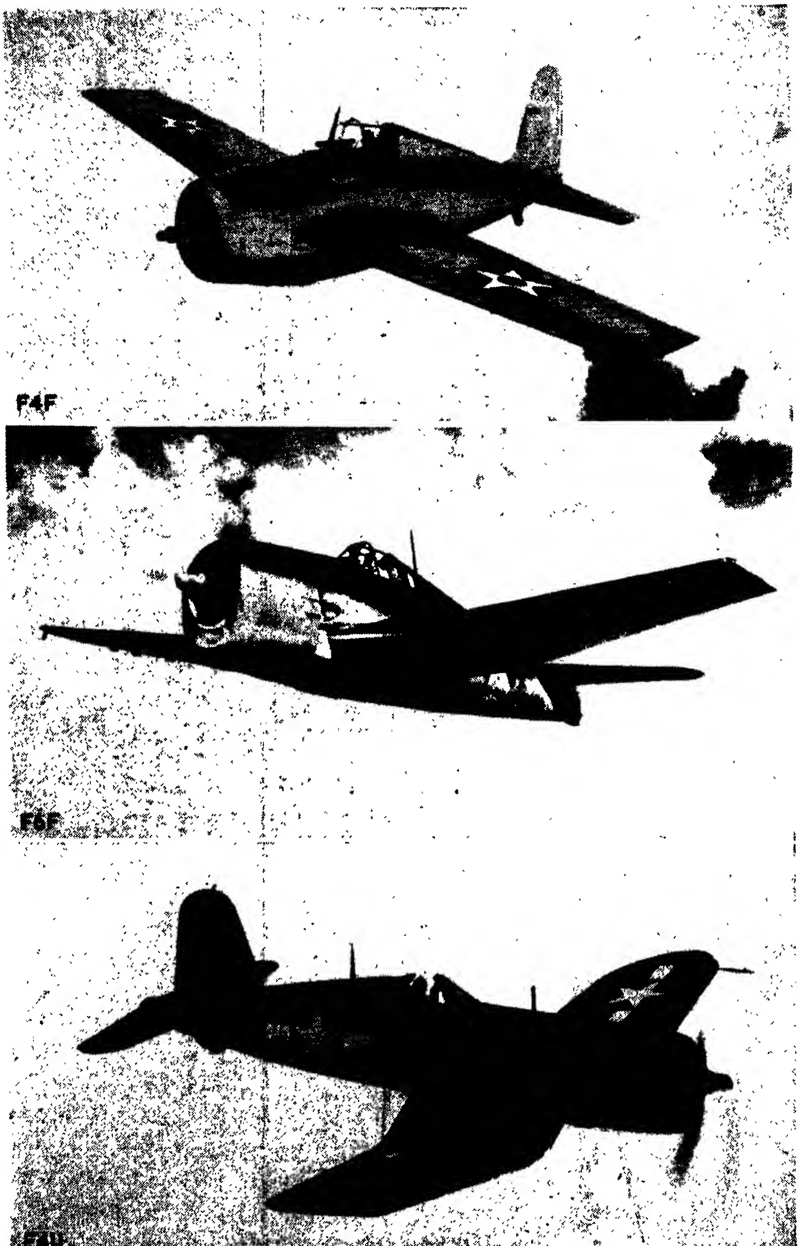


FIG. 216. Carrier-based fighters F4F, F6F, F4U. (*Official U.S. Navy photographs.*)

deflected. The brakes are needed to prevent dive velocities from becoming so large that the bomb must be released too high above target, with a loss in accuracy. The perforations reduce the shaking effect of the flap wake on the tail.

Figure 218 shows the larger dive bomber SB2C, or the Curtiss Helldiver, and the TBF, or Grumman Avenger, torpedo bomber. The Helldiver carries its normal bomb load internally. The Avenger car-

FIG. 217. Dive bomber, SBD. (*Official U.S. Navy photograph.*)

ried either a 21-in. torpedo or bombs up to 2,000 lb internally. It was the largest plane regularly based on aircraft carriers.

For land-based patrols, for either search, antisubmarine work, or bombing, naval aviation used modifications of the Liberator and the Lockheed-Vega Ventura, the PV1 (Fig. 219). This figure shows also the most used patrol boat, the Consolidated PBY Catalina (Cat); wing-tip floats are retracted to form wing tips in flight. Another long-range patrol bomber is the Martin Mariner PBM (Fig. 191).

The airplane carrier with its planes form the long-range striking force of the Navy. Important sea battles in the Second World War were fought without a gun on either side being fired at a ship. Skill of carrier operation played a major part in clearing the Pacific of the enemy. An *Essex*-class carrier is shown in Fig. 220 with Hellcat fighters and SB2C dive bombers spotted on the flight deck. On the port side for-

ward is the deck catapult for assisting take-off. Such a carrier is 880 ft long and carries 90 to 100 airplanes. An Avenger, flaps down, landing gear extended, is about to land on another carrier in Fig. 221; the *landing hook*, seen trailing at the tail between the wheels, is about to engage

Fig. 218. Torpedo bomber TBF; dive bomber SB2C. (*Official U.S. Navy photographs.*)

one of the *arresting-gear wires*. This wire is allowed to pull out slowly, stopping the plane within a short distance.

For scouting and observation from battleships and cruisers, small single-float seaplanes are launched by catapults (Fig. 222). After completing its mission, the plane lands on the water in the wake of the ship and is hoisted back on board by a crane. The plane shown is a Curtiss Seagull S03C.

For these combat planes, some dimensions are given in Table 13.

Also included are the numbers of each airplane built during 1940 to 1945 inclusive. Other combat planes built in large numbers were: Douglas A-20 Havoc, 7,440; Douglas A-26, 2,550; Bell P-39 Airacobra, 9,590; Bell P-63 Kingcobra 2,290; Curtiss P-40 Warhawk, 13,740. Transports, used also for air-borne troop carriers and glider tugs,

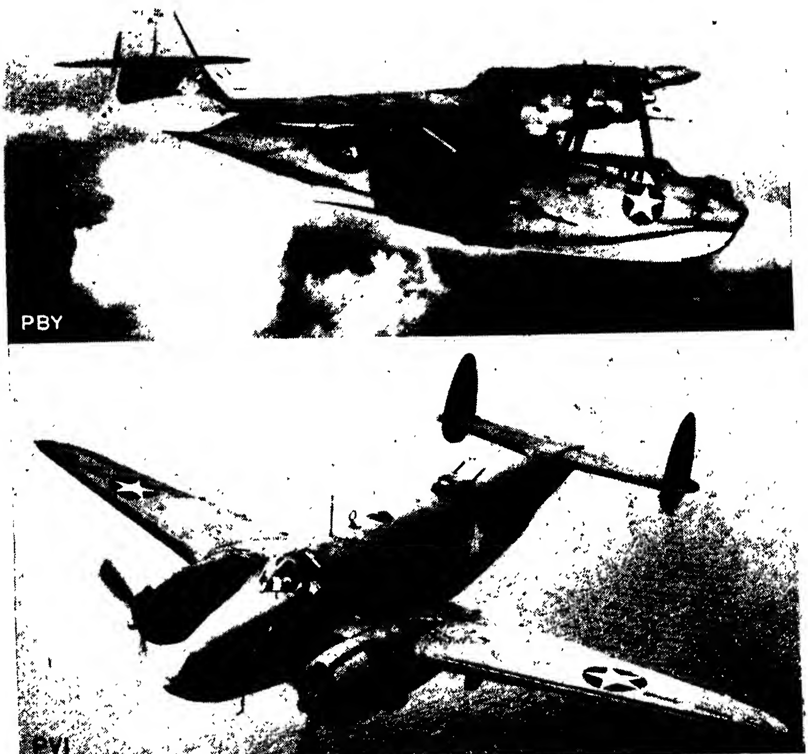


FIG. 219. Patrol bombers PBY flying boat; PV1 land plane. (*Official U.S. Navy photographs.*)

included: Douglas C-47, (DC-3), 9,400; C-54 (DC-4), 1,160; Curtiss Commando C-46, 3,180. Among the trainers were: Boeing-Wichita PT-13 (Fig. 2), 8,290; Fairchild PT-19, 7,800; North American Texan AT-6, 16,630; Consolidated Vultee Valiant BT-13, 11,540. Total number of airplanes built during the five years 1941 to 1945 was 297,200; the maximum number in one year was 96,300 in 1944.

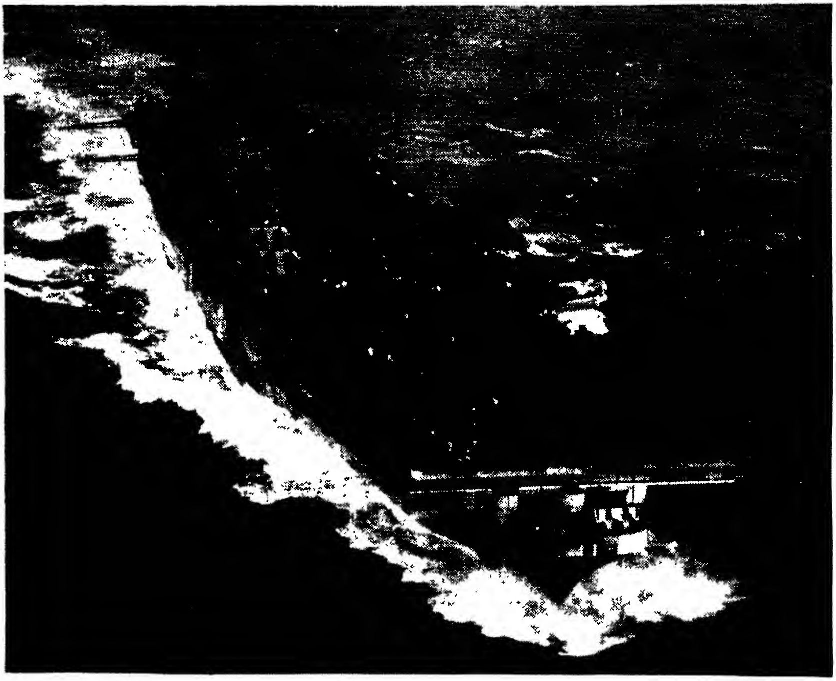


FIG. 220. *Essex*-class aircraft carrier. (*Official U.S. Navy photograph.*)

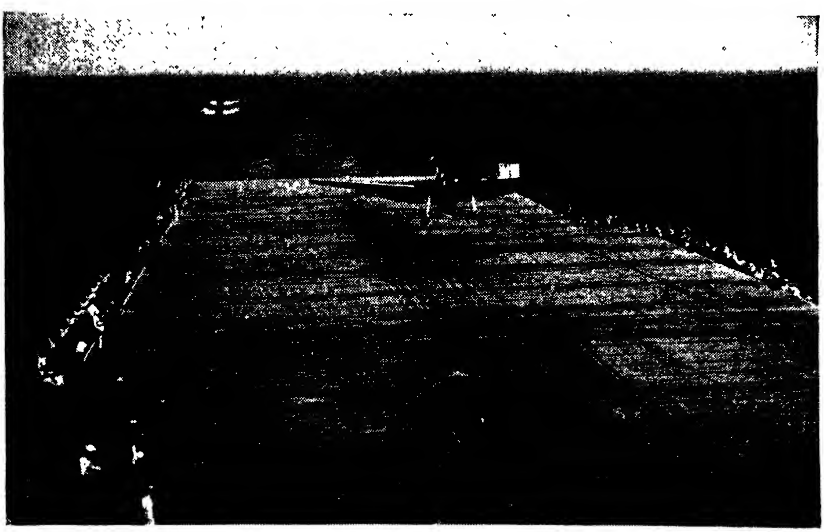


FIG. 221. TBF landing on aircraft carrier. (*Official U.S. Navy photograph.*)

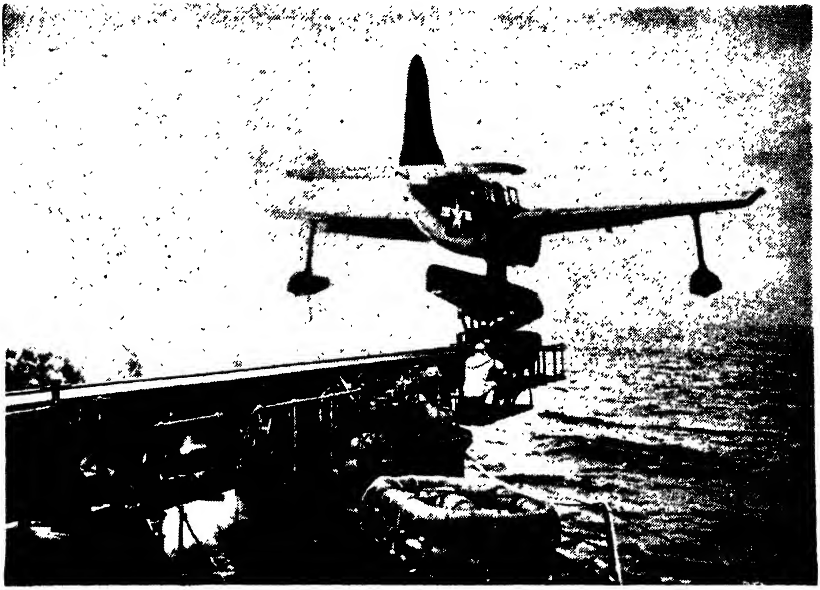


FIG. 222. SO3C launched by catapult. (*Official U.S. Navy photograph.*)

TABLE 13. CHARACTERISTICS OF SOME UNITED STATES MILITARY AIRPLANES OF THE SECOND WORLD WAR

Type	Designer	Model	Name	Span, ft	Wing area, sq ft	Weight, lb	Engines	Power at take-off, bhp	Number built 1940–1945
Pursuit	Lockheed	P-38	Lightning	52.0	328	18,000	2 Allison	3,000	10,000
	Republic	P-47	Thunderbolt	40.7	300	14,000	1 P & W	2,100	15,700
	North American	P-51	Mustang	37.4	233	8,600	1 Rolls-Royce	1,600	15,500
Bomber	North American	B-25	Mitchell	67.6	610	28,300	2 Wright	3,400	9,800
	Martin	B-26	Marauder	71	664	35,000	2 P & W	4,200	5,200
	Convair	B-24	Liberator	110	1,048	56,000	4 P & W	4,800	18,200
	Boeing	B-17	Flying Fortress	104	1,420	65,000	4 Wright	4,800	12,600
	Boeing	B-29	Superfortress	141	1,751	130,000	4 Wright	9,200	3,900
Fighter	Vought	F4U	Corsair	41.0	314	12,000	1 P & W	2,100	11,400
	Grumman	F6F	Hellcat	42.8	334	11,400	1 P & W	2,100	12,300
	Grumman	F4F	Wildcat	38.0	260	6,200	1 P & W	1,200	7,900
Bomber	Douglas	SBD	Dauntless	41.5	325	9,520	1 Wright	1,100	6,000
	Curtiss	SB2C	Helldiver	49.8	442	12,800	1 Wright	1,700	7,100
	Grumman	TBF	Avenger	54.2	490	15,000	1 Wright	1,700	9,800
	Lockheed	PV-1	Ventura	65.5	551	30,000	2 P & W	4,200	3,000
Patrol	Convair	PBY	Catalina	104	1,400	35,000	2 P & W	2,200	2,700
	Martin	PBM	Mariner	118	1,400	60,000	2 P & W	4,200	1,300

MODERN MILITARY PLANES

All those combat planes are obsolete, though many of some types are still in use. A few of the new types of military planes are developments of wartime planes. Such are the new model of the Corsair F4U-5 (Fig. 184), externally like the older F4U's but with more power and performance. A new Grumman carrier-based fighter is the F8F or Bearcat, small like a Wildcat, but carrying the engine and firepower of the Hellcat (Fig. 223).

FIG. 223. Navy fighter, F8F Bearcat. (*Grumman Aircraft Engineering Corporation.*)

For dive bombing and other forms of attack against ships and land targets, a larger plane, the AM-1 Mauler, has been developed by Martin for the Navy (Fig. 224). Though this airplane is a single-seater, bombs up to 4,000 lb, a torpedo, or rockets in various combinations can be carried, all on external racks. For strafing there are also four 20-mm cannon.

Another Navy plane, the Lockheed P2V Neptune (Fig. 225), is a larger, higher powered, and much-improved descendant of the Ventura. The most famed of the P2V's is the *Truculent Turtle*, which, flown by a Navy crew, left Perth, Australia, crossed the Pacific, and landed 55 hr and 17 min later at Columbus, Ohio. The distance, 11,236 statute miles, was the longest nonstop nonrefueling flight recorded to that time (Spring, 1948). At take-off the plane weighed 85,500 lb, 47 per cent more than its normal gross weight of 58,000 lb. Gasoline carried was

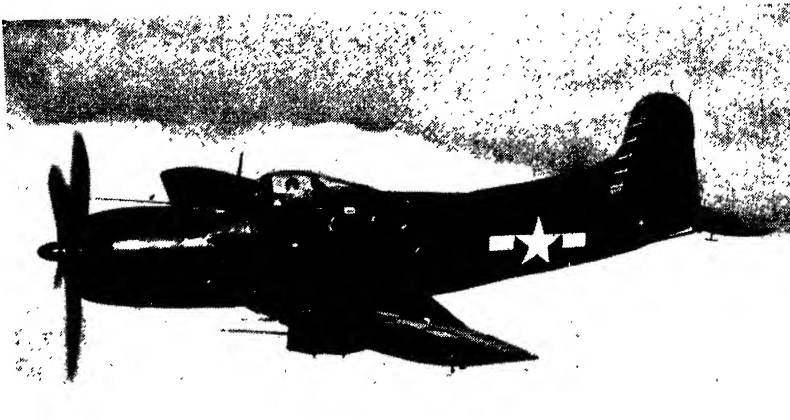


FIG. 224. Navy attack plane, AM-1 Mauler. (*The Glenn L. Martin Company.*)

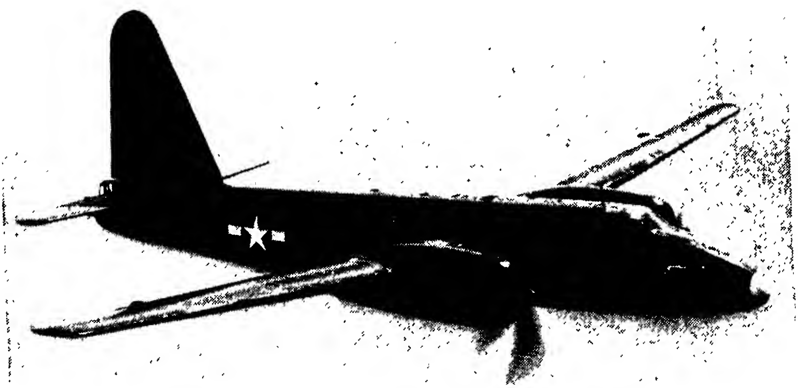


FIG. 225. Navy bomber, P2V Neptune (*Truculent Turtle*). (*Lockheed Aircraft Corporation.*)

8,467 gal, 59 per cent of the total weight at take-off. Part of the extra fuel was carried in droppable wing-tip tanks. Take-off was made in 4,800 ft by the two duplex Cyclone engines, rated at 2,500 bhp each, assisted by 4 jet-assist take-off rockets (Jato) giving 1,000 lb thrust each.

From the B-29 Superfortress, Boeing has developed the B-50 Superfortress for the Air Forces (Fig. 226). Many improvements in design, including substitution of stronger 75S aluminum alloy in wing skin,

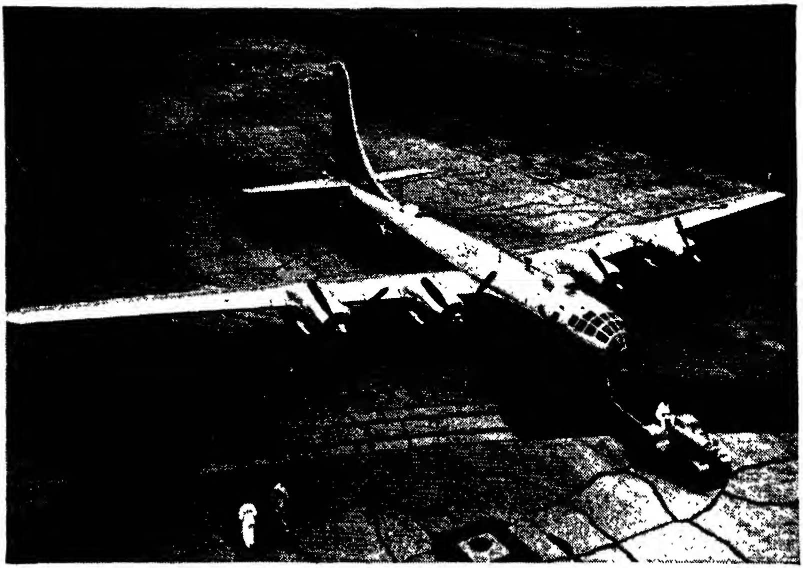


FIG. 226. Air Force bomber, B-50 Superfortress. (*Boeing Airplane Company.*)

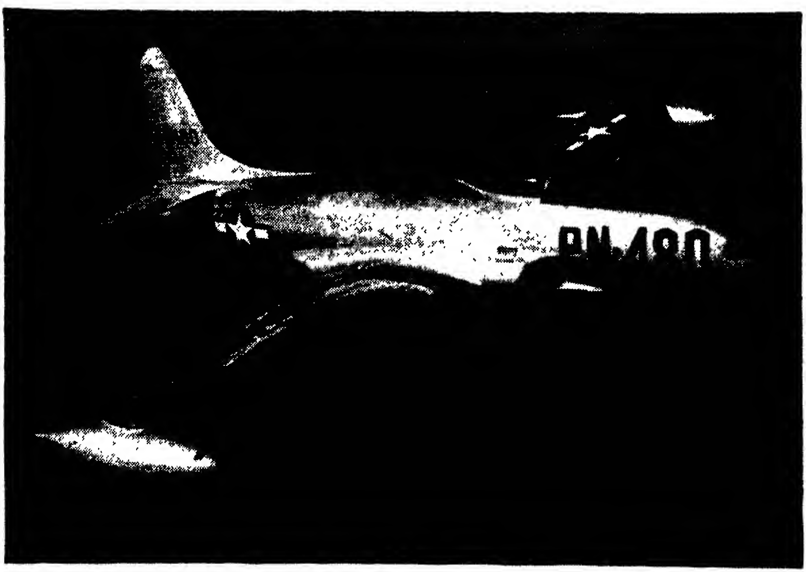


FIG. 227. Air Force pursuit plane, F-80 Shooting Star. (*Lockheed Aircraft Corporation.*)

have been made. The largest change is replacement of the Wright duplex Cyclone of the B-29's with Pratt & Whitney Wasp Major's in the B-50's. Gross weight is increased 15,000 lb, to about 145,000 lb. Cruising speed is increased 50 mph. A new vertical tail is so tall that its top must be hinged down to clear hangar doors. As in the B-29, crew spaces are pressurized, landing gear is tricycle; that on the B-50 retracts in 11 sec, much faster than on the B-29. Propellers are Curtiss Electric reversible.

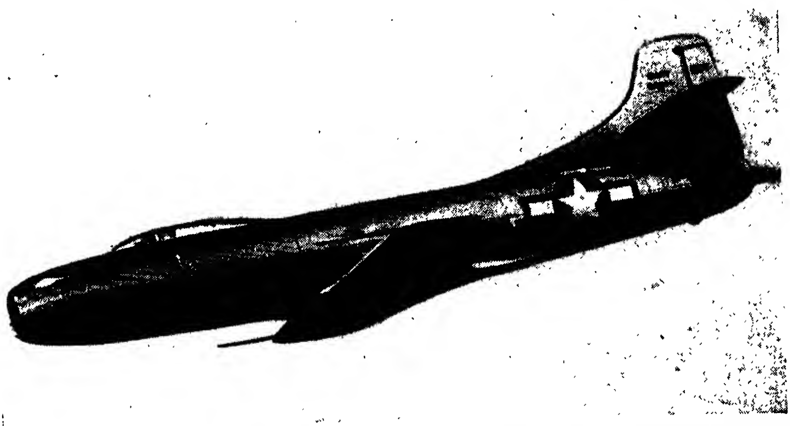


FIG. 228. Navy experimental plane, Douglas D-558 Skystreak. (*Official U.S. Navy photograph.*)

Other new military planes are radically different. All except the very largest have turbojet engines for power plants. For all except maximum range, the lighter power plant permits greatly increased performance.

Representative of the Air Forces jet-propelled single-seater pursuit planes is the first to be ordered in quantity, the F-80 Shooting Star built by Lockheed (Fig. 227). This plane is armed with six 50-caliber guns. The one shown has tip tanks to increase fuel supply. It has the dive flap under the fuselage deflected. This small flap can be deflected by the pilot to avoid any slowness of recovery from near-sonic-speed dives, during which most planes tend to dive more steeply. Water injection in the jet air intake permits extra thrust for take-off and short climbs. At the high speeds at which this plane flies, the temperature of the skin is raised to 150 or 200°F. The transparent canopy must be specially built to prevent warping. The cockpit is kept comfortably

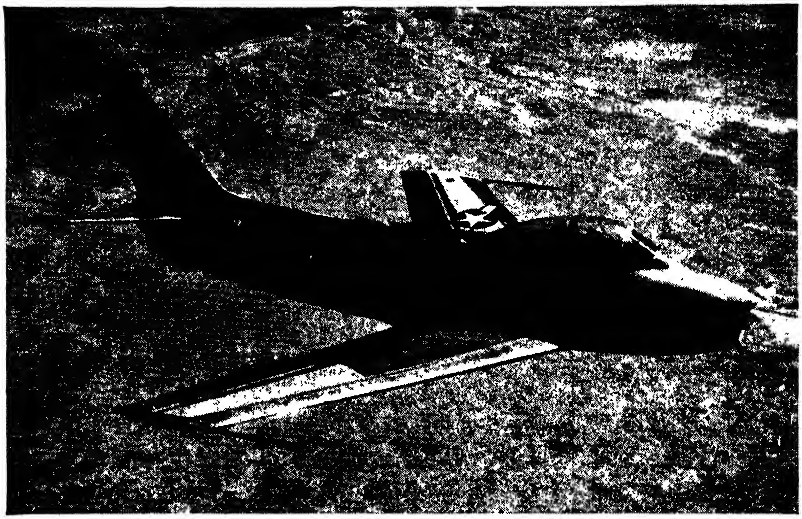


Fig. 228*A*. North American F-86 fighter. (*U.S. Army A.A.F. photograph.*)

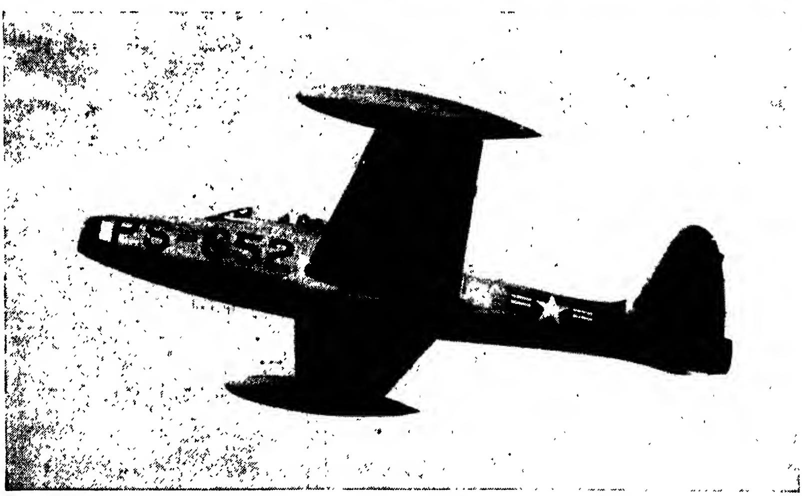


Fig. 229. Air Force pursuit plane, F-84 Thunderjet. (*Republic Aviation Corporation.*)

cool by a tiny refrigeration turbine. Since prolonged operation at high altitude is planned, the cockpit is pressurized. A slightly modified F-80 set a world's speed record of 624 mph for a 3-km course in June, 1947, only to have it broken twice in the last of August by the Douglas D-558 Skystreak, an experimental Navy transonic research plane (Fig. 228). This plane has a single General Electric axial-compressor

turbojet with nose air intake. Its speed for the record was successively 641 mph and 651 mph.[1] As successor to the P-47 Thunderbolt, many of the jet pursuit, F-84 Thunderjet, have been completed by Republic (Fig. 229). Recently the Air Forces have decided to change the name from pursuit plane to fighter.

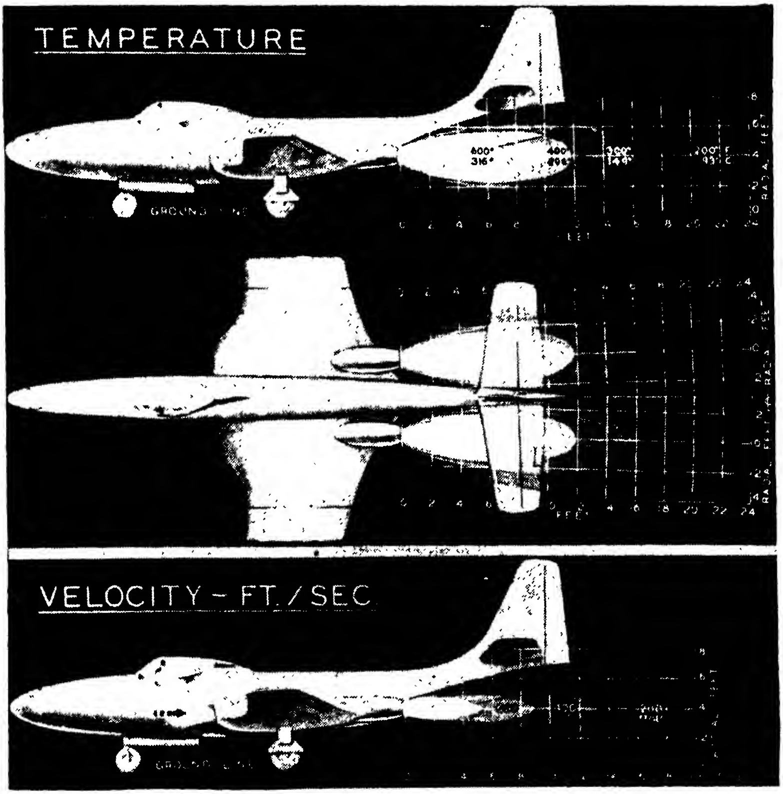


FIG. 230. Distribution of velocity and temperature behind a jet. (*McDonnell Aircraft Corporation.*)

For carrier-based turbojet fighters, many new problems are encountered: How closely may planes be spaced without setting the plane behind afire, or burning handling crews? How will lower thrust during take-off affect rapidity of getting planes aloft from the carrier? How will the less rapid decrease and increase of thrust with the throttle

[1] In September, 1948 a fully equipped fighter, the North American F-86, raised the speed record to 671 mph. This plane (Fig. 228A) has wing and tails swept back 35°.

opening affect landing on? The first question is partially answered by what appears a probable answer to the second; *i.e.*, that catapult assist seems superior to other take-off methods, and jets need not be run up to full power, hence temperature, before the plane is moved to the catapult. Figure 230 shows distribution of jet velocity and temperature behind the McDonnell Phantom. The velocity will blow a man away before he is burned. Another help is to make the front-wheel leg kneel, canting up the jets and tail as shown (Fig. 231). This also permits closer stowage when jets are not running by allowing the nose of the rear plane to project under the tail of the one in front.

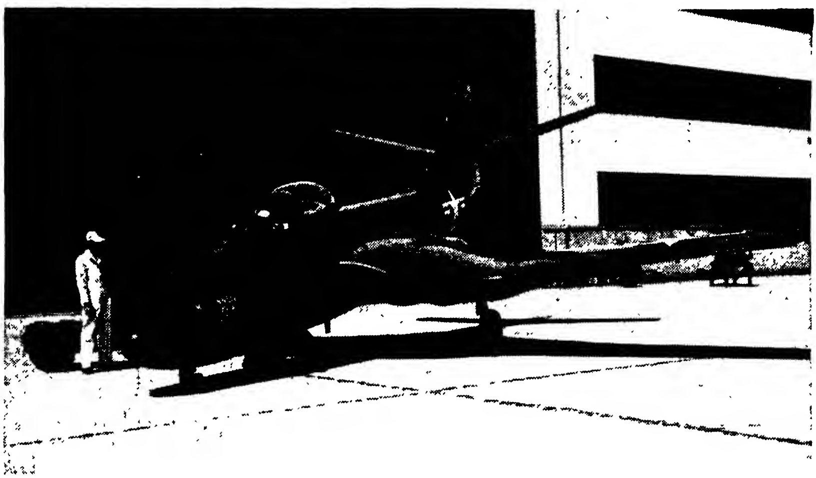


FIG. 231. Navy jet fighter with front-wheel leg lowered. (*McDonnell Aircraft Corporation.*)

In Fig. 232 are three of the Navy's carrier-based jet-propelled fighters. These illustrate different installation arrangements. The top one, the XF6U Pirate by Chance Vought, has a single Westinghouse jet in the fuselage with two air intakes, one on each wing root, and a single tail pipe below and forward of the stabilizer. The middle plane, the XF2H Banshee, by McDonnell, has twin Westinghouse 24 jets located in thickened wing roots with air intakes close to the fuselage and discharging at the trailing edge. The lower plane, the XFJ Fury by North American, has a single jet with straight-through airflow, intake at nose, jet under tail but well back (also shown in Fig. 48). Notice that on all three the air-speed measuring head is located near the top of the fin.

For the Banshee, a three-view sketch is shown (Fig. 233), while Fig.

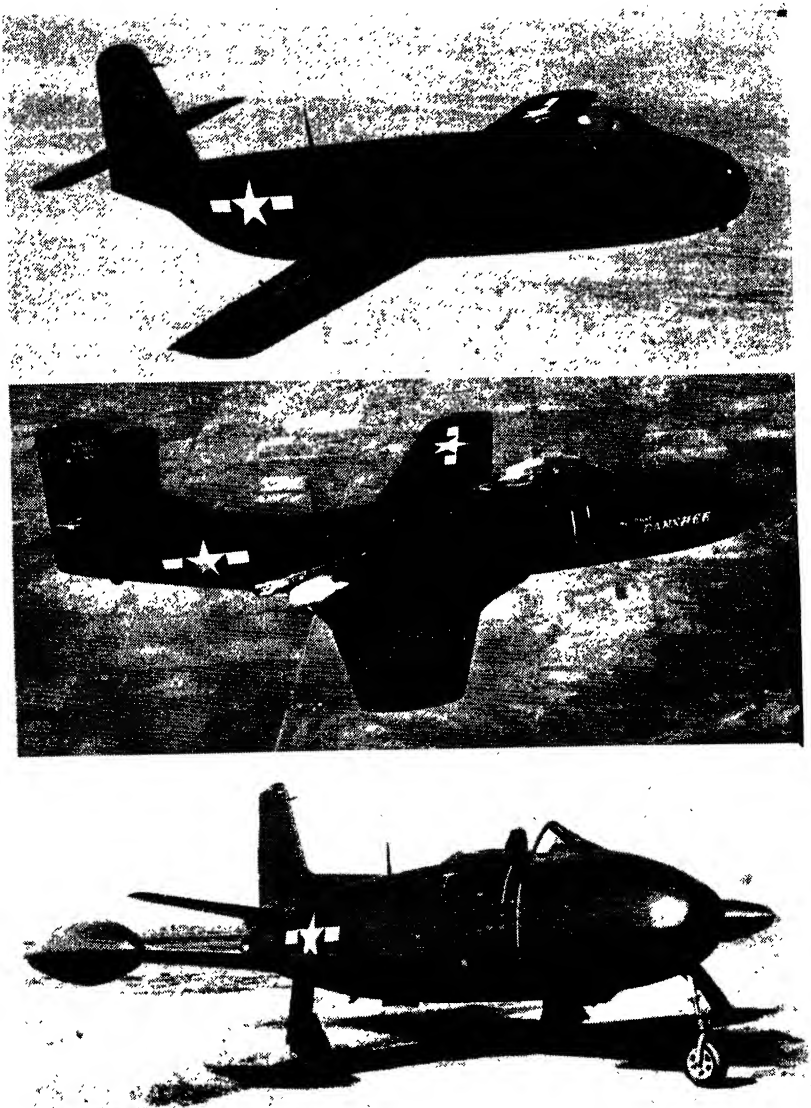


FIG. 232. Navy jet fighters XF6U, XF2H, XFJ. (*Chance Vought Aircraft; McDonnell Aircraft Corporation; official U.S. Navy photograph.*)

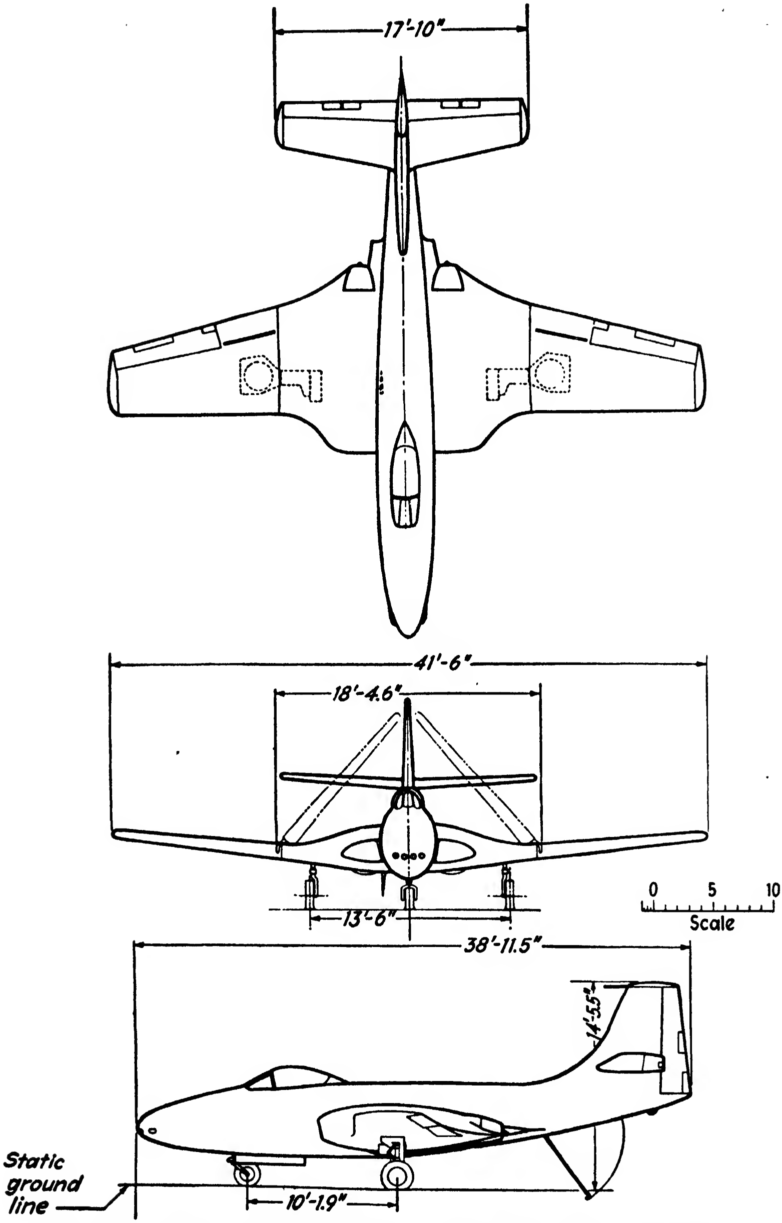


FIG. 233. Sketch of XF2H Banshee. (*McDonnell Aircraft Corporation.*)

234 shows the smaller FH Phantom divided into components. This plane has two smaller Westinghouse 19 jets. The Phantom is also shown in Fig. 1. The twin-jet plane has the same advantage that all twin-engine airplanes have: it can return safely on one jet if accident causes failure of the other. With the close spacing of jets of the FH and F2H, the thrust is so near the center that no trouble is experienced from asymmetric thrust with one jet working. In fact, the moment is so small that for cruising, recommended practice is to shut off one engine and thus use the other at nearly full load. Fuel economy of tur-

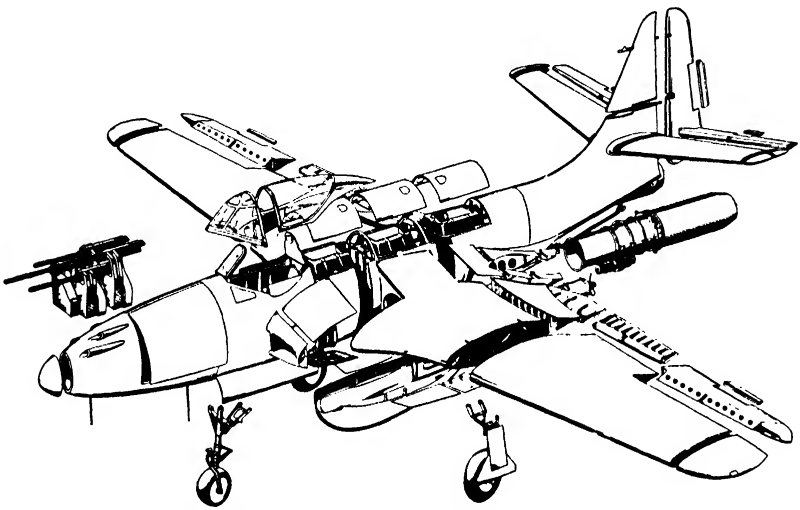


FIG. 234. Components of FH Phantom. (*McDonnell Aircraft Corporation.*)

bojets is best when they operate at nearly full load. Just as propellers on engines which are not running are feathered to reduce the drag and stop the engine rotation, so the rotation of a turbojet engine is stopped and its drag reduced when fuel is shut off, by a valve that closes off the air intake.

New-style medium bombers are larger than the older heavies, the B-17 or B-24. They are much faster with turbojet power plants. Figure 235 shows the XB-46, built by Consolidated Vultee, in flight and taxiing. This plane has really graceful lines. The four jets in two twin nacelles give maximum normal thrust of 16,000 lb. Wheels retract into nose and nacelles. The wing is extremely thin to allow the plane to attain high speed. Another jet bomber, XB-48, built by Martin, has been shown in Fig. 186. Again the extreme thinness of the wing is apparent. The six jets give about 24,000 lb thrust. More startling in appearance

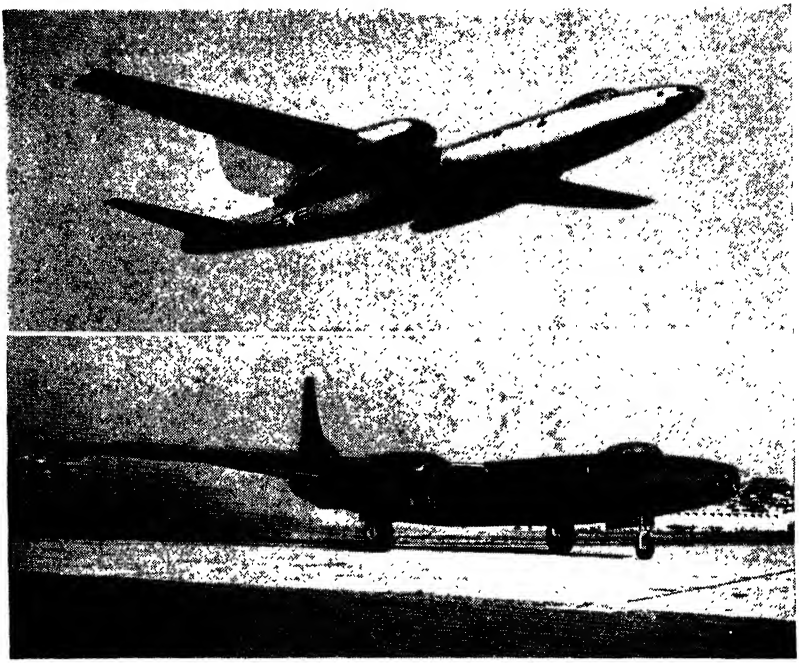


FIG. 235. Air Force bomber XB-46. (*Consolidated Vultee Aircraft Corporation.*)

FIG. 236. Air Force bomber XB-47. (*Boeing Airplane Company.*)

than either is the XB-47, a jet bomber built by Boeing (Fig. 236). Like the XB-48, it has a bicycle landing gear; but the jets on each side are located two on a thin "keel" under the wing at conventional nacelle location and one under the wing well out to the tip rather than three in

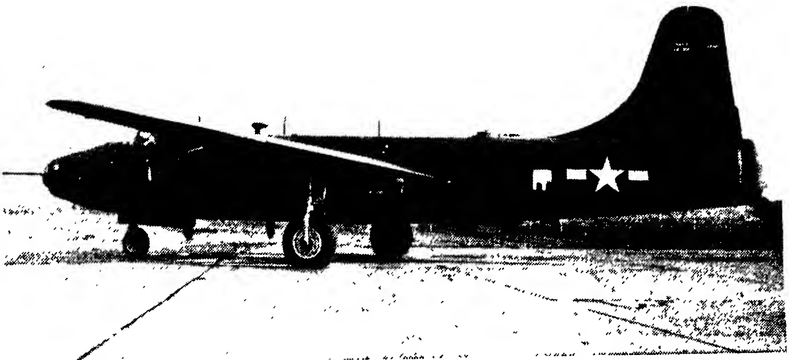


FIG. 237. Martin patrol plane XP4M. (*Official U.S. Navy photograph.*)

FIG. 238. Ryan Navy fighter, FR-1 Fireball. (*Official U.S. Navy photograph.*)

a triple nacelle as on the XB-48. As shown, the airplane is in landing configuration: gear out, flaps deflected, wing-tip slots open. All surfaces have 35° sweepback to help ensure a high critical Mach number. The six jets give a total thrust of about 24,000 lb.

To make use of the low fuel consumption of the reciprocating engine, yet achieve the higher speed and climb possible with turbojet engines, a

Navy patrol plane XP4M, built by Martin, has two Pratt & Whitney Wasp Majors of 3,000 bhp or more each and two Allison J-33 turbojets. As shown in Fig. 237, the propeller engines are in conventional nacelles with the turbojet engines beneath them. Maximum range is over 3,000 miles, using the reciprocating engines only, except for take-off. A similar combination is in a fighter, FR-1, the Ryan Fireball (Fig. 238). The engine is a Wright Cyclone of 1,350 bhp and the jet a General Electric I-16.

The largest bomber of the Air Forces, the Convair B-36, is a six-engine, pusher-type, high-wing monoplane with pressurized fuselage.

FIG. 239. Air Force bomber B-36. (*Consolidated Vultee Aircraft Corporation.*)

Its size can be judged from Fig. 239. Later models have double dual wheels in place of the huge single ones. The six Wasp Major engines give maximum speed of over 300 mph and maximum range of 10,000 miles with 10,000 lb of bombs. However, the B-36 can carry up to 72,000 lb of bombs for shorter ranges. Propellers are three-blade Curtiss electric, reversible. The pusher propellers suffer some vibration, particularly when flaps are extended. This plane is shown in flight in Fig. 4.

Another Air Forces bomber is the Flying Wing, XB-35, built by Northrop. This plane is large enough to take advantage of the lower drag made possible by the omission of fuselage and tails. The only projections (Figs. 240 and 241) from the wing are a bubble canopy for the pilots, small flat turrets for guns, and nacelles for gunners, in addition to the shaft fairings. The four turbosupercharged Wasp Major engines themselves are wholly within the wing. Propellers are eight-

FIG. 240. Air Force bomber XB-35 Flying Wing, top view. (*Northrop Aircraft, Inc.*)

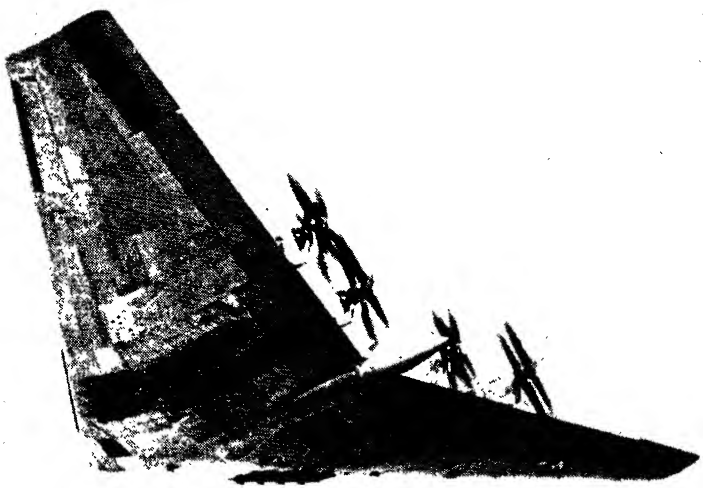


FIG. 241. Air Force bomber XB-35 Flying Wing, bottom view. (*Northrop Aircraft, Inc.*)

blade Hamilton Standard counterrotating pushers, 15 ft 4 in. in diameter, driven by extension shafts. The combination of pushers, long shafts, and counterrotating gears has caused serious vibration troubles; later planes will have single-rotation propellers to change resonant conditions. For controls, the trailing edge is divided into three sections: the inner is for landing flaps; the sections outboard of the engines, called ***elevons***, combine the functions of elevators when moved together

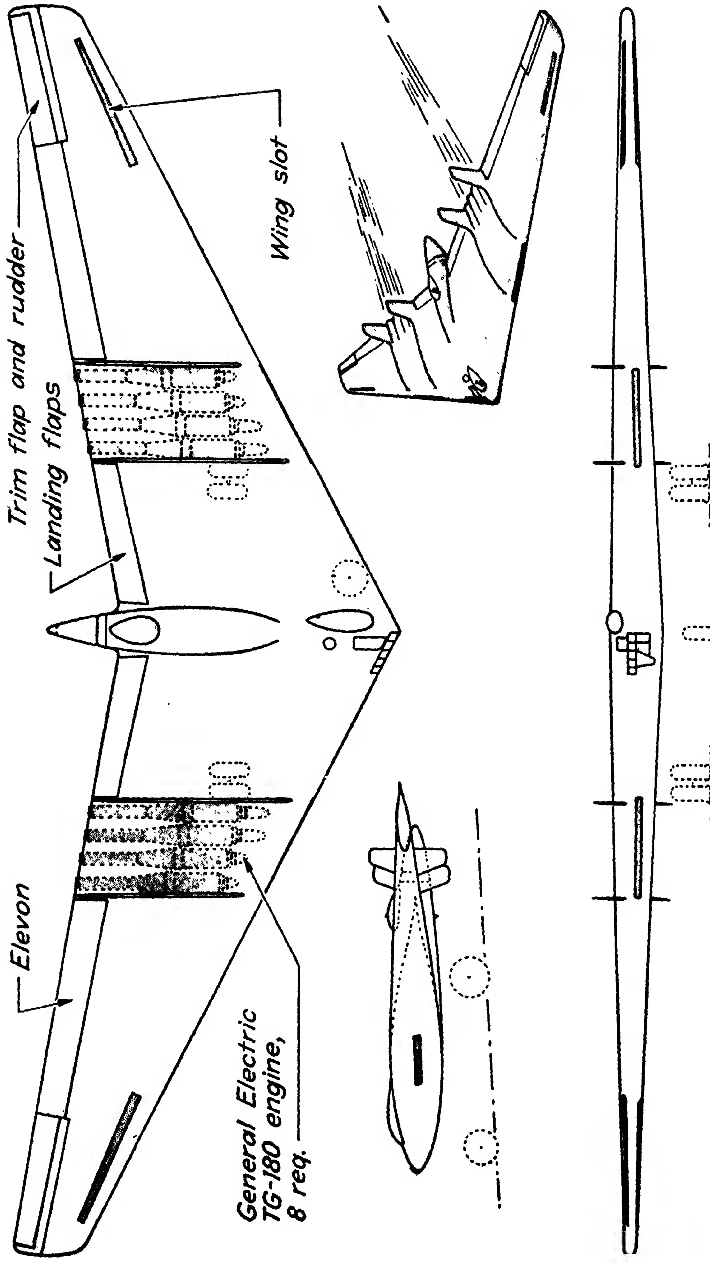


FIG. 242. Sketch of Air Force bomber YB-49. (*Northrop Aircraft, Inc.*)

and ailerons when moved differentially, the outer section acts as a trim flap to offset changes in the position of the center of gravity. Besides this, the trailing edges of the outer section may be separated on one side at a time to add to the drag of that side producing a yawing movement, hence acting in place of the rudder of a conventional plane. "Rudder" effectiveness is maintained and stalling delayed by a wing slot that is closed at high speed to reduce drag. All controls are operated through hydraulic boosts. The counterrotating pusher propellers act as fins to provide longitudinal and some directional stability even though there are no fixed surfaces. This effect will be reduced when single-rotation propellers replace the counterrotating ones, and is lost

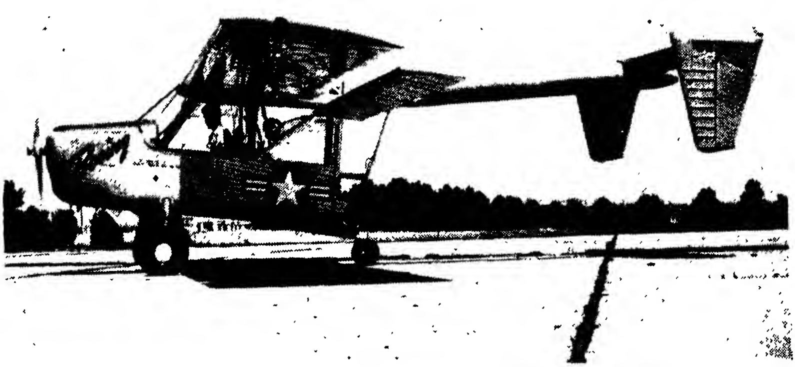


FIG. 243. Army liaison plane XL-15. *(Boeing Airplane Company.)*

altogether in the turbojet version, B-49 (Fig. 242). This jet-propelled bomber is the B-35 with eight General Electric axial-flow jet engines replacing the four reciprocating engines. To provide the necessary directional stability, fins with low air fences or separators in front of each are placed inboard and outboard of the group of four jets on each side of the plane. Performance of the B-49 is much improved, since at high speeds the eight jets have over twice the thrust of the four reciprocating engines, yet they weigh less. Maximum range, however, is greater for the reciprocating-engine model. For this flying wing, structural weight is low, drag is low, and the long-range performance is good.

At the opposite end of the size scale is an unconventional little liaison plane, XL-15, built by Boeing-Wichita for the Air Forces (Fig. 243). Designed for shell spotting and other liaison duties involving operation with ground troops, this airplane has the following features: It has clear view all around and ability to operate from a cleared pasture or even a

wire stretched between two poles. To ensure a low landing speed and to aid take-off, the wing has a permanent external flap. The 125-hp Lycoming engine gives take-off over a 50-ft obstacle in 500 ft. The plane is strong enough to be towed as a glider up to 165 mph and is readily disassembled to pack into a 2½-ton army truck.

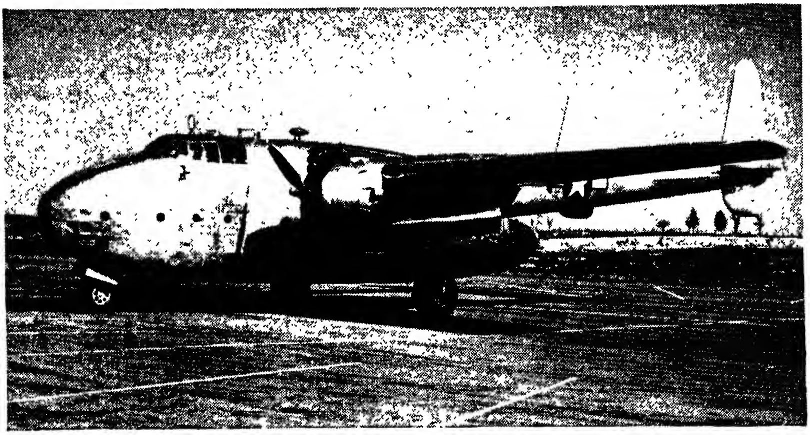


FIG. 244. Fairchild transport C-82 Packet. (*U.S. Army A.A.F. photograph.*)

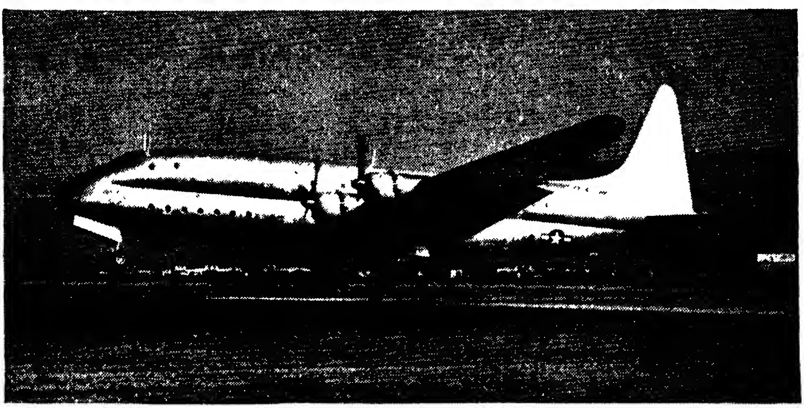


FIG. 245. Navy long-range transport, XR60 Constitution. (*Lockheed Aircraft Corporation.*)

Military transports for goods or air-borne troops are not considered combat aircraft, but their cargoes of weapons and combat teams play an important part in future offensive and defensive tactics. One example of such a transport is the Fairchild C-82 Packet (Fig. 244), a peculiar-looking huge fuselage with a clear space 38 ft 6 in. long by 8 ft

TABLE 14. CHARACTERISTICS OF SOME UNITED STATES MILITARY AIRPLANES

Airplanes with Reciprocating Engines and Propellers

Type	Builder	Model	Name	Span, ft	Wing area, sq ft	Weight, lb	Engines	Take-off, bhp*
Fighter	Grumman	F8F	Bearcat	35 5	....	9 500	1 P & W	2,200
Bomber	Martin	AM-1	Mauler	50	496	21,000	1 P & W	3,200
	Lockheed	P2V	Neptune	75 5	1,000	58,000	2 Wright	5,000
	Boeing	B-50	Superfortress	141	1,751	145,000	4 P & W	13,000
	Northrop	XB-35	Flying Wing	172	4,000	209,000	4 P & W	12,000
	Convair	B-36	....	230	4,772	278,000	6 P & W	18,000
Combat transport	Fairchild	C-82	Packet	107	1,400	50,000	2 P & W	4,200
Transport	Lockheed	XR60	Constitution	189	...	184,000	4 P & W	12,000
Liason	Boeing	XL-15	....	40 0	...	2,050	1 Lycom.	125

Airplanes with Both Propellers and Turbojets

Type	Builder	Model	Name	Span, ft	Wing area, sq ft	Weight, lb	Engines	Take-off bhp + thrust, lb*
Fighter	Ryan	FR-1	Fireball	40.0	.	9,860	1 P & W 1 GE	1,350 1,600
Patrol	Martin	XP4M	Mercator	114	1,300	80,700	2 P & W 2 Allison	6,000 8,000

Airplanes with Turbojet Engines

Type	Builder	Model	Name	Span, ft	Wing area, sq ft	Weight, lb	Engines	Take-off thrust, lb*
Pursuit	Lockheed	F-80	Shooting Star	38 5	237	14,000	1 Allison	4,000+
	Republic	F-84	Thunderjet	36	..	13,000	1 Allison	4,000+
Experimental	Douglas	D-558	Skystreak	25	150	9,750	1 GE	4,000+
Fighter	Vought	XF6U	Pirate	30 2	....	....	1 West.	
	McDonnell	FH	Phantom	40 8	.....	10,000	2 West.	3,200
	McDonnell	XF2H	Banshee	41 5	....	14,000	2 West.	
Bomber	Convair	XB-46	....	113	..	91,000	4 GE	16,000
Bomber	Boeing	XB-47	Stratojet	116	1,428	125,000	6 GE	24,000
Bomber	Martin	XB-48	....	108	. .	....	6 GE	24,000
Bomber	Northrop	YB-49	Flying Wing	172	4,000	200,000+	8 GE	32,000

* All take-off bhp and thrust may be increased by water injection.

1 in. wide by 8 ft 5 in. high at back dropping to 6 ft 5 in. at front, carried along by a wing. On the wing are two Pratt & Whitney 2,100-hp engines with nacelles extended back as booms to support the tail. This is a case of "functional design" or "handsome is as handsome does." The Packet has been adopted as standard combat carrier for para-

troops, equipment, air-borne infantry, and other services to aid the Army.

Much larger and resembling conventional four-engine air liners is the Lockheed Constitution, Navy XR60 (Fig. 245). This plane is intended as a long-range transport rather than a combat carrier. Fuselage is pressurized with figure-of-eight section. Engines are Pratt & Whitney Wasp Majors giving 3,000 bhp each. Propellers are Curtiss electric, 19 ft in diameter, with the inboard pair reversible. All controls have hydraulic boosts. All engines and "plumbing" can be reached for minor maintenance while in flight. Main wheels of the double tandem landing gear are prerotated before landing, allowing savings of tire weight. The four wheels on a side permit use of runways designed for smaller planes. De-icing of wings, stabilizer, and fin is by heat from exchangers in the engine exhaust. Cabin heat is from same source. The plane carries 10,000 gal of gas, a crew of 12, and up to 190 passengers.

Wing spans, weights, and engines of the newer planes are listed in Table 14.

Flights at supersonic speeds at high altitudes were first made by Air Forces and NACA pilots in the XS-1, a tiny experimental rocket-driven monoplane, in October, 1947. This plane is launched from a B-29 at high altitude. Further discussion of supersonic piloted planes must be postponed.

CHAPTER XVII

AIRCRAFT INSTRUMENTS AND ACCESSORIES

Aircraft instruments may be divided into four classes: power-plant instruments, flight instruments, navigating instruments, and miscellaneous instruments.

POWER-PLANT INSTRUMENTS

The purpose of the power-plant instruments is to indicate to the pilot or flight engineer the condition of the engine and of the other parts of the power plant, and to assist him in operating them properly.

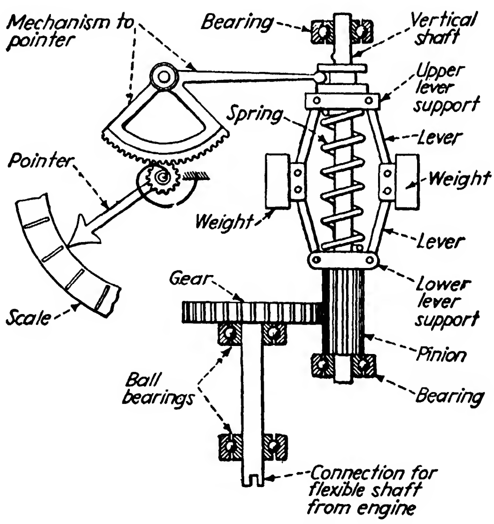


FIG. 246. Diagram of centrifugal tachometer mechanism.

The Tachometer. This is an instrument for indicating the speed of the engine crankshaft. It is, perhaps, the most important power-plant instrument and is used in practically every type of aircraft and with every type of engine.

Small single-engine aircraft generally use the *centrifugal*-type tachometer diagrammatically illustrated in Fig. 246. A vertical shaft

inside the tachometer casing is driven from the engine by means of a long flexible shaft contained within a flexible tubular casing. Mounted on the vertical shaft are weights arranged on levers so that they can move in and out radially from the shaft axis. When the tachometer is at rest, the weights are held in their innermost position by a coiled spring, which surrounds the shaft and presses on the upper lever support. This support is so arranged that it can slide up and down along the vertical shaft. When the engine rotates the tachometer shaft, cen-

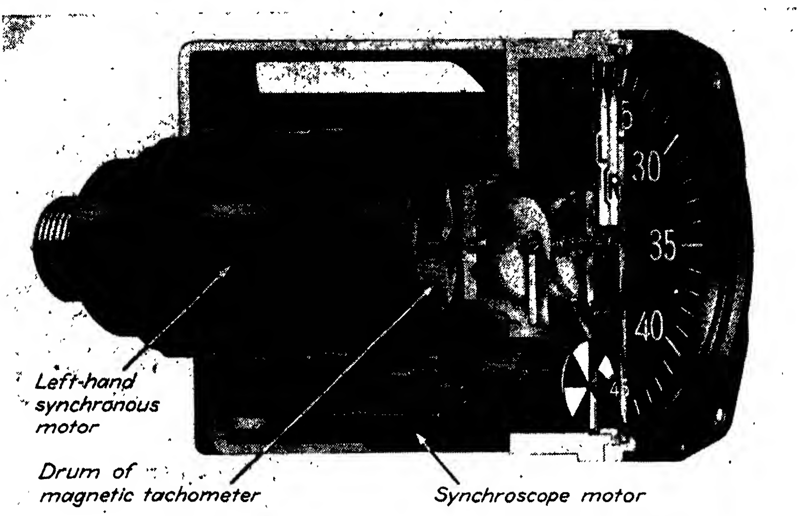


Fig. 247. Dual electric tachometer indicator with synchroscope. (*Kollsman Instrument Division, Square D Company.*)

trifugal force causes the weights to move outward. This pulls down the upper lever support and compresses the spring. At any speed, there is a position of equilibrium where the centrifugal force of the weights just balances the spring pressure. The position of the upper lever support is communicated, through suitable mechanism, to the pointer of the instrument, which moves over a scale marked in rpm.

In the *magnetic tachometer*, the flexible shaft from the engine rotates a small permanent magnet. The poles of this magnet pass close to the face of a metal disc or drum (see Fig. 247) that is free to turn against a spring and whose motion is transmitted to a pointer through suitable gearing. The faster the magnet rotates, the greater will be the magnetic *drag* on the disc and the farther it will turn against the resistance of the spring. Thus, the position of the pointer indicates speed of engine rotation, and the dial can be calibrated in engine rpm.

Electric tachometers are generally used in multi-engined airplanes, and even in single-engined airplanes where the distance between engine and instrument board is long. This type of tachometer comprises a small electric generator driven by the engine and connected by wires to an indicator on the instrument board. The generator is usually of the three-phase a-c type. The *indicator* (Fig. 247) contains a three-phase *synchronous* motor. A synchronous motor is one that always operates at a speed proportional to the frequency of an alternating current, which means, in this case, that the motor speed is always the same as the generator speed. The indicator of the instrument contains not only the motor, but also a magnetic tachometer which translates the motor speed into position of a pointer on a dial calibrated in engine rpm.

Figure 247 shows a cutaway view and Fig. 248 shows the face of the indicator element of an electric tachometer. This particular instrument is designed for use with two engines and incorporates two synchronous motors in one casing. Each tachometer operates one of the two concentric pointers. In addition, this particular instrument is equipped with a *synchroscope*, or device for indicating whether the two engines are running at the same speed.

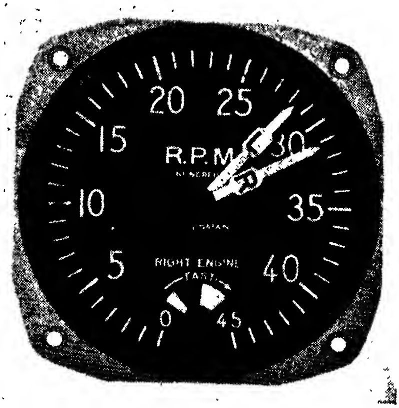


FIG. 248. Face of dual electric tachometer indicator with synchroscope. (*Kollsman Instrument Division, Square D Company.*)

In flight there are disagreeable *beats* of sound and vibration when the engines are not *synchronized*, *i.e.*, when they are not running at exactly the same speed. The synchroscope motor is connected to the two tachometer motors in such a way that it rotates to the right when the right engine is faster than the left engine, and rotates to the left when the opposite is true. When both engines are running at the same speed, the synchroscope motor is stationary. A small striped disc is mounted on the synchroscope motor shaft and is visible through an opening in the face of the dial (Fig. 248).

Automatic Engine Synchronizer. In airplanes with more than two engines, automatic synchronizers are sometimes used. In such devices the three-phase current from all the tachometer generators is connected to a control mechanism which adjusts the propeller governors so as to

synchronize the engines. This mechanism is, of course, thrown out of operation when it is desired to run the engines at different speeds, as in taxiing.

Pressure Gages. Pressure gages are used in airplanes for indicating various fluid pressures. The gages used are generally of two types, the *bourdon* gage used for measuring relatively high pressures, and the *diaphragm* gage used for measuring relatively low pressures.

The Bourdon Pressure Gage. This gage, illustrated by Fig. 249, is used for indicating oil pressures, fuel pressures, etc., and is also used in connection with *distance thermometers*, as will be explained later. The characteristic element of this type of gage is the *bourdon tube*, which is made of some relatively thin metal, usually bronze, and which has an oval cross section (see Fig. 249). This tube is bent in the form of an incomplete circle, the flat sides of the tube being at right angles to the plane of the circle. The free end of the tube is closed, and the other end is fastened to the instrument case and is connected by means of an external pipe to the fluid whose pressure is to be indicated. An increase of pressure of the fluid tends to increase the diameter of the tube circle. This gives the closed end of the tube a motion which can be transmitted to a pointer through suitable gearing, as shown. The dial may be marked in various ways, depending on the purpose for which the gage is to be used. For measuring oil pressure, fuel pressure, etc., the gage dial is generally marked in pounds per square inch for American and British airplanes; whereas for other airplanes the dial is marked in metric units.

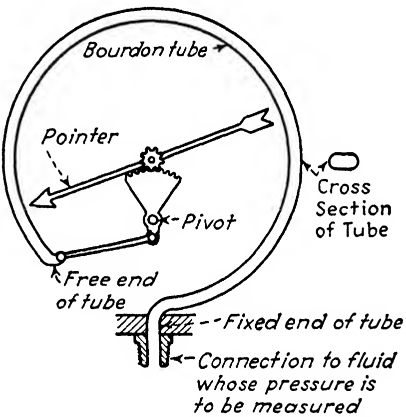


FIG. 249. Bourdon-type pressure gage, diagram showing internal construction.

The Diaphragm Pressure Gage. For the measurement of relatively low pressures, it has been found that an element made up of one or more thin diaphragms is more suitable than a bourdon tube. Figure 250 illustrates the internal arrangement of a gage of this type. The diaphragm element D in this case is made of two thin metal discs joined so as to form a flat circular chamber. There are two pressure connections, A to the inside of the diaphragm element and B to the interior of

the instrument case. The expansion or contraction of the diaphragm element evidently depends on the difference in pressure existing between the connections A and B. If B is open to the atmosphere, the motion of the diaphragm will be proportional to the difference between the pressure applied to A and the atmospheric pressure. The motion

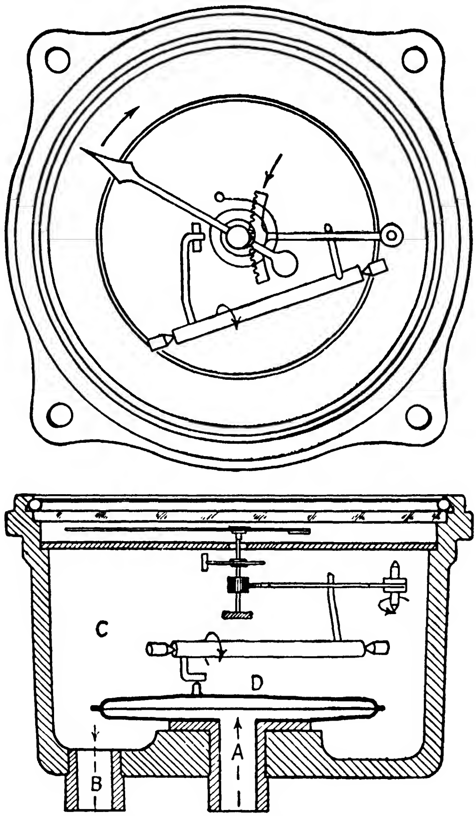


FIG. 250. Diaphragm pressure gage. (*Pioneer Instrument Division, Bendix Aviation Corporation.*)

of the diaphragm is transmitted to the pointer through a mechanical system, such as that shown in the figure.

Engine Thermometers. Since the engine is usually located at a considerable distance from the pilot's instrument board, it is seldom possible to use the ordinary mercury thermometer in airplanes. The thermometers used are generally of the *distance* type, where the bulb of the thermometer is at some distance from the indicating dial. Most

distance-type thermometers, like the mercury thermometer, depend for their action upon the expansion and contraction of a liquid. This liquid is contained in a bulb, which is placed at the point where temperature measurement is desired. The bulb is connected, through a long, very fine tube, called a *capillary*, to the indicating instrument, which is a small pressure gage of the bourdon type. A diagram of a distance-type thermometer is shown in Fig. 251. In some makes, both the bulb and capillary are filled with liquid, while in other makes, the liquid is used in the bulb only, and the pressure of the vapor above the liquid, which varies with temperature, is used to operate the pressure gage. In either case, the dial on the pressure gage is marked in degrees Fahrenheit or centigrade, rather than in units of pressure. Thermometers of this kind are used to indicate water temperature, oil temperature, and intake air temperature.

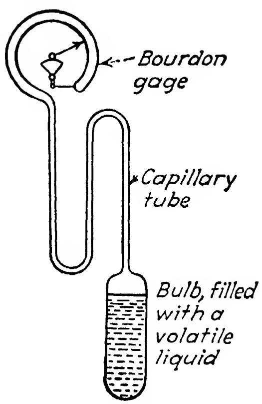
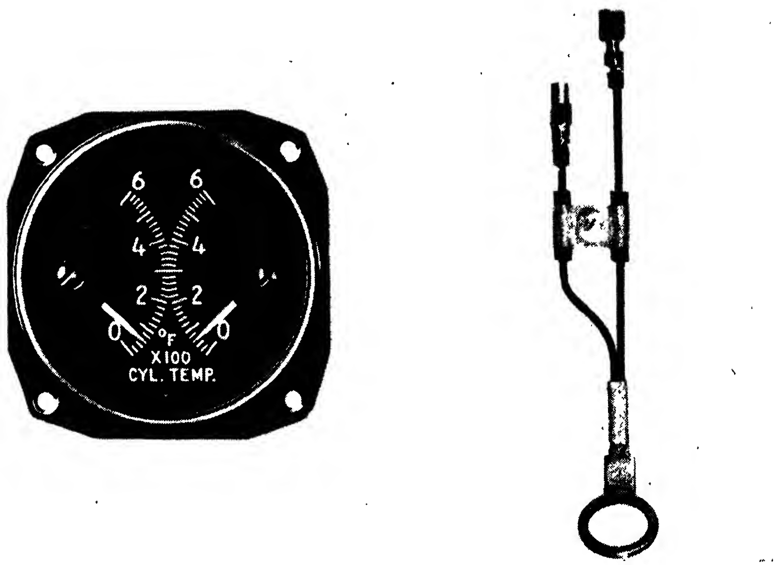


FIG. 251. Distance thermometer, vapor-pressure type.

Thermometers of the foregoing types are often used for other purposes than engine temperatures. One such case is that of measuring atmospheric temperature, in which case the bulb is located at some convenient place in the air away from the fuselage. Another use for such instruments is to operate automatic temperature controllers. In such cases, motion of the pressure-gage element operates an electric switch or a hydraulic valve, which, in turn, operates the controlling mechanism.

Thermocouple Temperature Indicator (Fig. 252). For measuring relatively high temperatures, particularly the temperatures of air-cooled cylinders, a *thermocouple* is preferable to other types of thermometer. A thermocouple depends for its action on the fact that when two different metals are placed in electrical contact with each other, a small electromotive force (voltage) is produced between them, and this force increases with temperature. The instrument consists of two insulated wires of suitable material to form the two elements of the couple. At one end these wires are embedded close together in the metal whose temperature is to be measured. This is usually some point of high temperature on one cylinder of the engine, or it may be a copper spark-plug washer which, when clamped between the spark plug and the cylinder, assumes approximately the temperature of the latter. The other ends of the thermocouple wires are connected to a *millivolt-*



(a) (b)

FIG. 252. Thermocouple temperature indicator. (a) Indicating unit. (*Weston Electrical Instrument Corporation.*) (b) Spark-plug gasket thermocouple. (*Thermo Electric Company.*)

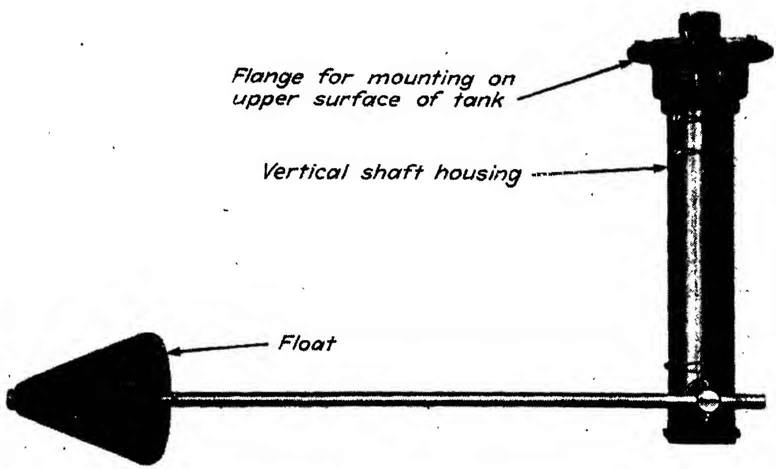


FIG. 253. Fuel-level gage, remote type. (*Pioneer Instrument Division, Bendix Aviation Corporation.*)

meter (one millivolt is one-thousandth of a volt) whose dial is marked in units of temperature.

Gasoline-level Gages. In all airplanes it is desirable to provide an instrument to indicate to the pilot the level of the gasoline in the fuel tank. If the fuel tank is in a suitable location, such an indicator may be simply a gage glass, similar to the gage glass used on a steam boiler. Unfortunately, the tank is usually located so that some more elaborate form of indicator is necessary. Most gasoline-level gages are operated by a float which is carried on the surface of the gasoline in the tank and which is connected to an indicating dial by a suitable mechanism.

Figure 253 shows the tank element of such an indicator. Motion of the float is converted to rotation of a vertical shaft which projects through the mounting flange. Position of the shaft may be transmitted to a dial either by mechanical means or by an electric system for remote indication (see page 346).

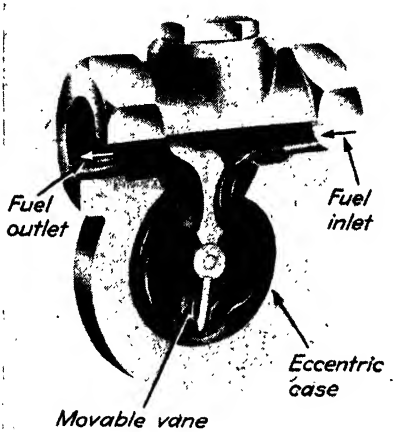


FIG. 254. Fuel flowmeter. (*Eclipse-Pioneer Division, Bendix Aviation Corporation.*)

In pump-operated fuel systems, a **fuel-flow indicator** is desirable to indicate whether or not the pump is functioning properly. The fact that fuel is flowing is usually indicated by a bourdon pressure gage connected into the fuel line near the carburetor or near the injection-pump supply line.

Fuel Flowmeter. It is often convenient, especially in test work, to have an instrument which will indicate the rate at which fuel is flowing to the engine. Such an instrument is known as a fuel flowmeter. One class of such instruments depends on a spring-loaded or gravity-loaded movable member, moving in a variable-area passage through which the fuel must flow. In Fig. 254 this member is a small spring-loaded vane which rotates in a spiral-shaped housing. The end of the vane and the circumference of the housing form a slot of variable area through which the fuel must flow. When fuel flows, it moves the vane to a position which depends on the rate of flow. The position of the vane is indi-

cated by rotation of the vane shaft, which may be transmitted to a pointer by mechanical or electrical means.

A fuel-air meter is an instrument for indicating the fuel-air ratio which is being supplied to the engine cylinders. This device enables

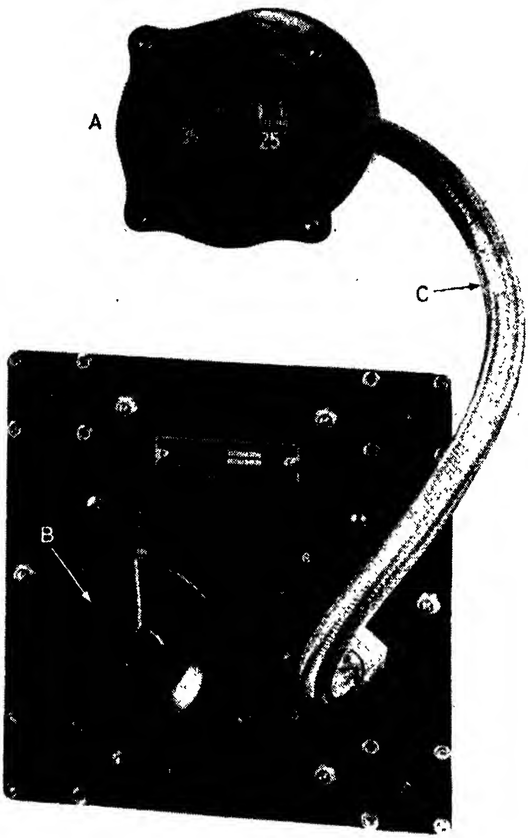


FIG. 255. Single-engine fuel-air meter or exhaust-gas analyzer. *A* Indicator. *B* Analysis cell. *C* Leads, in a flexible conduit. (*Cambridge Instrument Company, Inc.*)

the pilot to set his carburetor mixture control to give the proper mixture for any particular flight condition, or to make sure that an automatic mixture control is working properly. The fuel-air meter shown in Fig. 255 depends for its functioning on the fact that the composition of the exhaust gases, and hence their heat conductivity, varies with the mixture ratio. Exhaust gases from the exhaust pipe of the engine are

allowed to flow through a small tube to the sensitive element, which consists of a series of small, electrically heated wires. The exhaust gases surround one set of wires and air from the atmosphere surrounds the other set. The electrical circuit is so arranged that the difference in electrical resistance of the two coils, due to their difference in temperature, gives a reading on the instrument dial located in the cockpit. Rich mixtures give exhaust gases having a higher heat conductivity than air; thus they cool the wires in the exhaust gas more effectively than the wires in air are cooled. Lean mixtures have the opposite effect. Thus, the instrument dial can be calibrated in terms of fuel-air ratio.

Detonation Indicator. Since the sound of detonation (see page 151) cannot usually be heard by the flight crew, on account of other noise, an

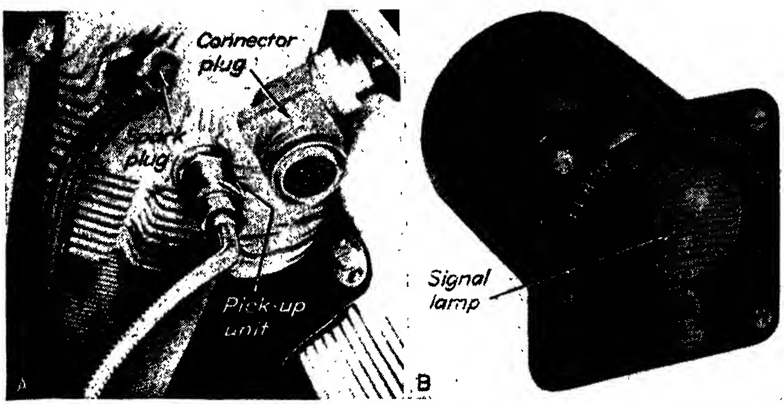


Fig. 256. Detonation indicator. (*a*) Pickup unit mounted on air-cooled cylinder head. (*b*) Indicator, mounted on instrument panel. (*Sperry Gyroscope Company.*)

indicator is necessary if detonation is to be detected in flight. The indicator shown in Fig. 256 depends for its operation on the fact that detonation sets up intense high-frequency vibrations of the cylinder head. Vibrations of the cylinder head are translated into electric-voltage fluctuations in a pickup unit mounted on the cylinder head (Fig. 256*a*). The fluctuating voltage is passed through an amplifier and other suitable circuits so as to light a signal lamp on the instrument board (Fig. 256*b*) when the cylinder-head vibrations characteristic of detonation are "picked-up" by the cylinder unit.

Electrical engine instruments, usually *ammeters* and *voltmeters*, may be used to indicate the performance of generators, batteries, and other electrical equipment used in connection with the power plant. Such

instruments are so well known as not to require detailed description here. They are made as small and as light as possible for airplane use.

Warning Signals. Owing to the large number of instruments and controls in a multi-engined airplane, the instruments which indicate correct functioning (such as oil pressure, fuel pressure, electric voltage, cylinder temperature, oil temperature, etc.) are often supplemented by a panel of *warning signals*. There are small lamps connected to automatic switches in such a way as to show a red light when the value of the quantity in question departs from its normal operating range.

FLIGHT INSTRUMENTS

Altimeter. The altimeter, used to indicate the altitude of the airplane, is the most important flight instrument. It depends for its

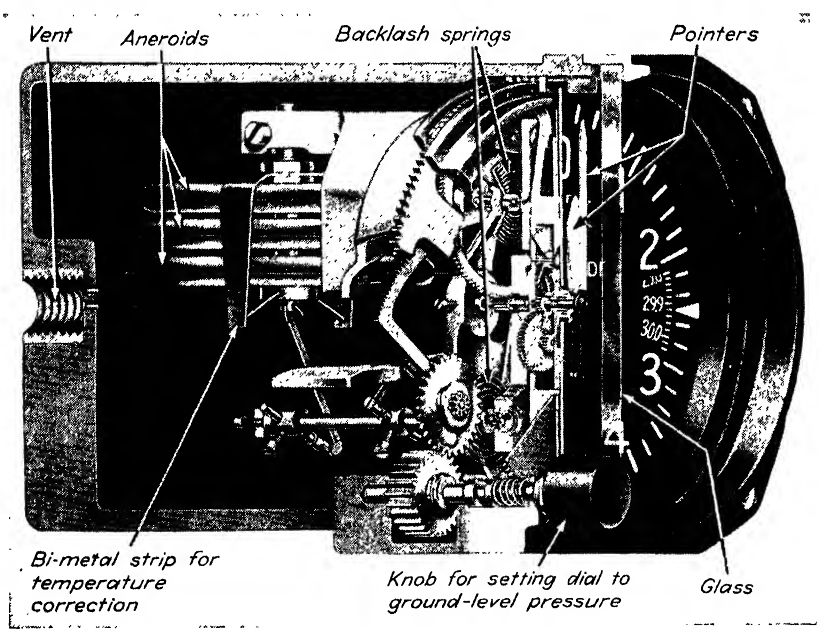


FIG. 257. Altimeter—cutaway view. (*Kollsman Instrument Division, Square D Company.*)

operation on the fact that air pressure varies with altitude, and it is simply a pressure gage with a dial reading in feet above sea level.

The internal arrangement of a typical altimeter is shown in Fig. 257. It is essentially a diaphragm pressure gage with diaphragm chambers exhausted of air and sealed. This type of diaphragm chamber is called an *aneroid*. In Fig. 257 three aneroids are shown, but many altimeters

use only one or two. The air is exhausted as completely as possible from the inside of the aneroids, since if the aneroids contained air, they would be sensitive to temperature changes as well as to pressure changes. The pressure of the atmosphere tends to press the two flat sides of the aneroids together, and this force is counteracted by the elasticity of the diaphragms. The length of the assembly of aneroids, therefore, depends on the atmospheric pressure, and the motion which takes place as the pressure on the aneroids is changed is transmitted through gearing to one or two pointers which move over a scale marked in feet above sea level. A bimetallic strip is used to correct the instrument for the expansion or contraction of the metal parts which occurs with changes in temperature.

FIG. 258. Face of sensitive altimeter. (*Kollsman Instrument Division, Square D Company.*)

The instrument illustrated (Fig. 258) is of the *sensitive* type. It has three pointers geared together like the hands of a sweep-second hand watch. For the shortest pointer the last number passed is tens of thousands feet altitude above sea level; for the middle pointer the numbers are additional thousands of feet; for the longest the numbers are hundreds of feet and the graduations 20 ft each. Hence the reading in the figure is 17,850 ft.

Unfortunately, the atmospheric pressure is not always the same at a given altitude, so that the indications of an altimeter require correction for local atmospheric conditions. To facilitate such correction, the dial of the instrument is arranged so that it can be turned by means of a knob (see figures). Behind the dial, and visible through a hole cut through it, is a scale of ground-level pressure, usually given in inches of mercury. When the dial is turned to a pressure reading corresponding to a certain point on the ground, the instrument reads very closely the height above that point. For example, when notified by radio of the "altimeter setting" at the airport at which a landing is to be made, a pilot can adjust his altimeter to read quite accurately his height above that point. The instrument illustrated is arranged so that the dial can be set for sea-level pressure, with additional indicators (small white markers in figure) which can be set to the field altitude.

Altimeters are made with an airtight casing in which is a vent to admit atmospheric pressure. Care must be used to be sure that pressure due to motion of the airplane through the air is not transmitted to the vent. If necessary, the vent is connected by tubing to a suitable location free from such influences.

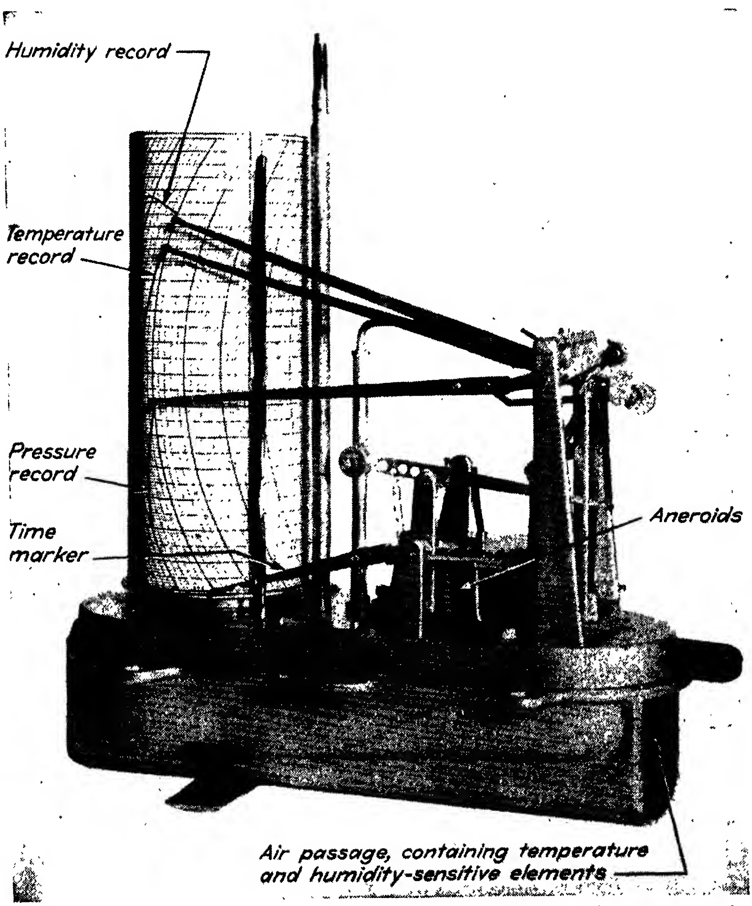


FIG. 259. Meteorograph. (*Friez Instrument Division, Bendix Aviation Corporation.*)

Barograph. An altimeter which records its altitude by drawing a line on a moving strip of paper is called a *barograph*. Such an instrument is useful where a permanent record of altitude throughout a flight is desired. The barograph is quite generally used for test flights and for altitude-record flights. It is operated by an aneroid, as in the case

of the altimeter, and the motion is transmitted to a pen which draws a line on a strip of paper. This strip of paper is moved at uniform speed by a clock mechanism which must be wound before the flight starts. It is often combined, in the same casing, with a recording thermometer and a *hygrometer* (an instrument for recording the relative humidity) so that simultaneous records of pressure, temperature, and humidity are made on the same chart. This combination of instruments is called a *meteorograph.* Figure 259 shows such an instrument, together with a copy of its record.

An **absolute altimeter** is a device for determining the distance of an airplane above the ground. Since the ordinary altimeter works by means of atmospheric pressure, it is not affected by the height of the ground beneath it, and it cannot warn against dangerously high terrain. The absolute altimeter, or "terrain-clearance" indicator works on the principle of the "reflection" of ultra-high-frequency radio waves from the ground. It consists essentially of a transmitter, which sends out the waves, and a device to measure the time between sending and receiving and to indicate it on a dial in terms of feet above the ground. The time is indirectly measured by measuring the phase relation of the sending and receiving waves. The instrument is necessarily somewhat complicated and is not generally used for ordinary flying.

Air-speed Indicators. An air-speed indicator is an instrument for indicating the speed of the airplane through the air. Next to the altimeter, it is the most important flight instrument. The air-speed indicator is essentially a diaphragm pressure gage operated by the difference in pressure between a *pitot tube* and a *static tube,* located in the air stream at some distance from the wings and fuselage.

A typical *pitot-static tube* is shown in Fig. 260. It consists of a central tube open at the end and facing forward in the direction of flight. Surrounding this tube is the static tube, closed at the forward end but having small holes at right angles to its axis. The interiors of these two tubes are connected, respectively, to two connections on the indicator (Fig. 261), which is a diaphragm pressure gage with dial marked in miles per hour. The action of the tubes depends upon the fact that the pressure in the tube facing in the direction of flight varies with the velocity of the air which strikes it, while the pressure in the static tube is independent of air velocity, the small holes being at right angles to the motion of the air. The difference in pressure between the static and the pitot tube is thus a measure of the speed of the airplane through the air, and the pressure gage to which they are connected may be marked in miles per hour or other suitable units of speed.

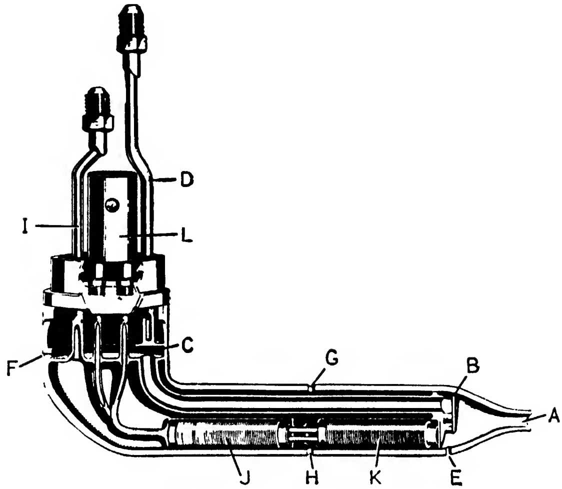


FIG. 260. Pitot-static tube.

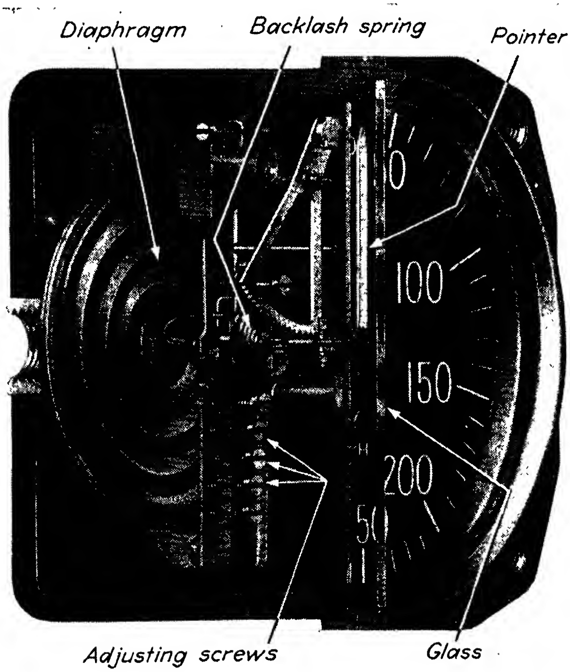


FIG. 261. Air-speed indicator, cutaway view. (*Kollsman Instrument Division, Square D Company.*)

As we have seen (page 17), the air pressure due to forward motion is nearly proportional to dv^2, where d is the atmospheric density and v is the airplane velocity. Thus, the speed indicated on the dial will depend on air density as well as on forward speed, and the reading is called *indicated air speed.* However, since stalling speed and general flight characteristics of an airplane are proportional to indicated air speed this characteristic of the air-speed meter is generally a desirable one.

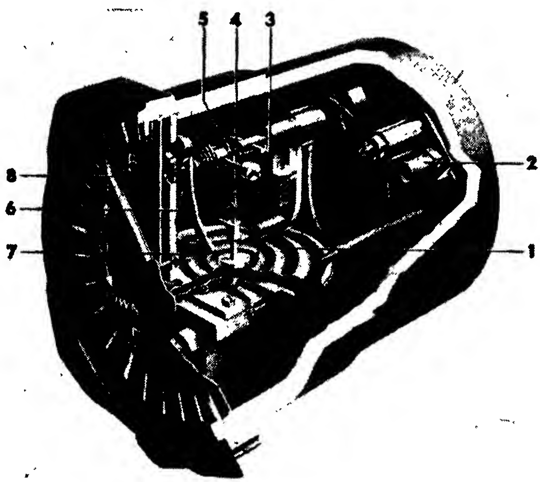


FIG. 262. Rate-of-climb indicator. (*Eclipse-Pioneer Division, Bendix Aviation Corporation.*)

1. Diaphragm
2. Diffuser
3. Link
4. Lever
5. Shaft
6. Quadrant
7. Pinion
8. Pointer

One difficulty with pitot tubes in the past has been their tendency to clog with water or ice. To prevent this, the tube shown in Fig. 260 is provided with an electric heating coil, supplied with current from the generator-battery system, and with a rather elaborate system of water baffles and drains. It is obvious that the air-speed indicator does not indicate speed over the ground except near sea level in still air.

Rate-of-climb Indicator. This instrument (Fig. 262) consists essentially of a diaphragm pressure gage enclosed in an airtight casing. The interior of the diaphragm is connected directly to the static pressure line of the pitot-static tube, and the interior of the casing is connected to the same line, but through a porous porcelain diaphragm called a *capillary.* If the airplane remains at the given altitude, the pressure in the case will equalize with the atmospheric pressure through the cap-

illary, and the pointer on the dial will read zero. However, when the atmospheric pressure on the inside of the diaphragm unit is changing rapidly, owing to climb or descent, the pressure inside the case changes at a less rapid rate, owing to the retarding effect on airflow of the capillary. Thus the diaphragm element will be subjected to a difference in pressure and a consequent deflection, which is a function of the rate at which the altitude is changing. The dial of the instrument is calibrated in feet per minute of ascent or descent, depending upon the direction in which the deflection takes place.

GYROSCOPIC FLIGHT INSTRUMENTS

A very important class of flight instruments depends on the action of a *gyroscope*, which is a small flywheel rotated at very high speed by an electric motor or by a small *air turbine.*

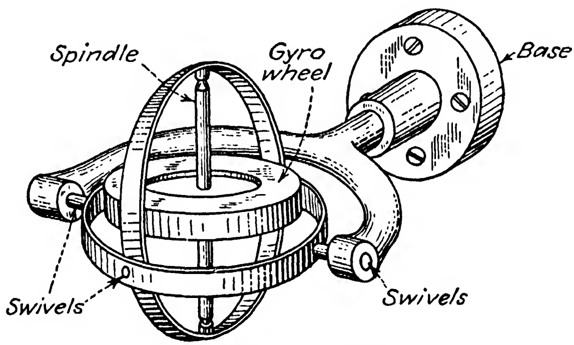


FIG. 263. Freely mounted gyroscope.

Gyroscopic instruments can be divided into two classes, namely, those used to indicate angular *position* of the airplane, *i.e.*, *attitude* and *direction*, and those used to indicate angular *motion* of the airplane, such as its rate of turn about a given axis.

Gyroscopic Position Instruments. The useful characteristic of a gyroscope, or *gyro*, is the fact that it resists any tendency to change the angle of its axis in space. To utilize this characteristic in position instruments, the gyro must be *free*, *i.e.*, it must be mounted in a frame in such a way that the base of the frame, or the member which is attached to the airplane, can be turned in any direction without turning the gyro. Such an arrangement is shown in Fig. 263 with the gyro shaft, or *spindle*, in the vertical position. If the gyrowheel is started in rotation in this position, it will remain with its spindle vertical in spite of any motion of the base, provided the swivel bearings, *i.e.*, the bearings

in the mounting, are frictionless. The same would be true if the gyro were started with its spindle in the horizontal, or any other position. Friction in the swivel bearings and the influence of the earth's rotation tend to change the gyro's position, but these effects act very slowly and can be corrected by occasional adjustment.

The *free* gyro, mounted as shown in Fig. 263 constitutes the basic control element of all *position*-indicating instruments, including the

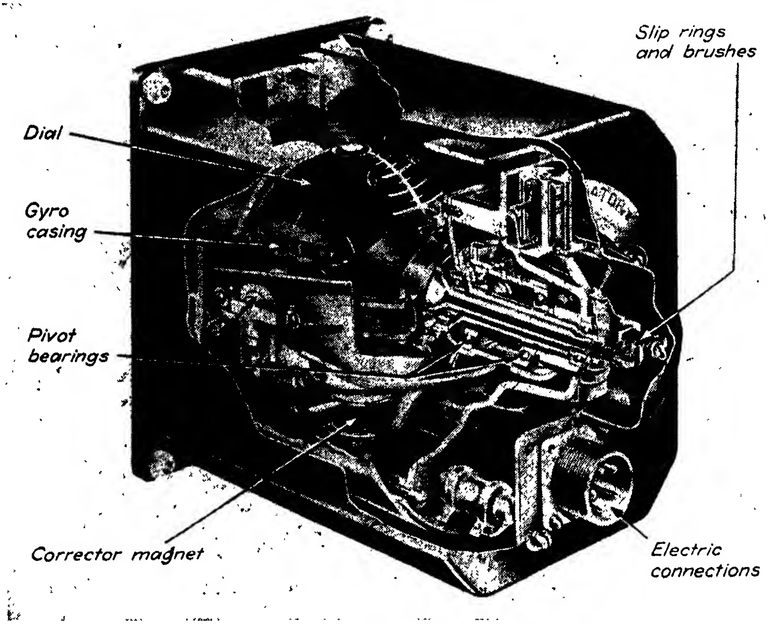


FIG. 264. Attitude gyroscope. (*Sperry Gyroscope Company.*)

attitude gyro or *artificial horizon*, the *directional* gyro, and the *gyrocompass*. It also constitutes the main controlling element of an *automatic pilot*.

In the *attitude gyro* (Fig. 264) or *artificial-horizon* type of instrument, the spindle remains in the vertical position. An indicator mechanism is attached to the frame and base in such a way as to indicate the *angle of the base*, *i.e.*, the *attitude* of the airplane, with respect to the vertical spindle. Figure 265 shows how these indications look to a pilot. A special electromagnetic mechanism corrects for swivel bearing friction and thus keeps the spindle from drifting away from the vertical position.

In the *directional gyro* the spindle is kept in the horizontal position

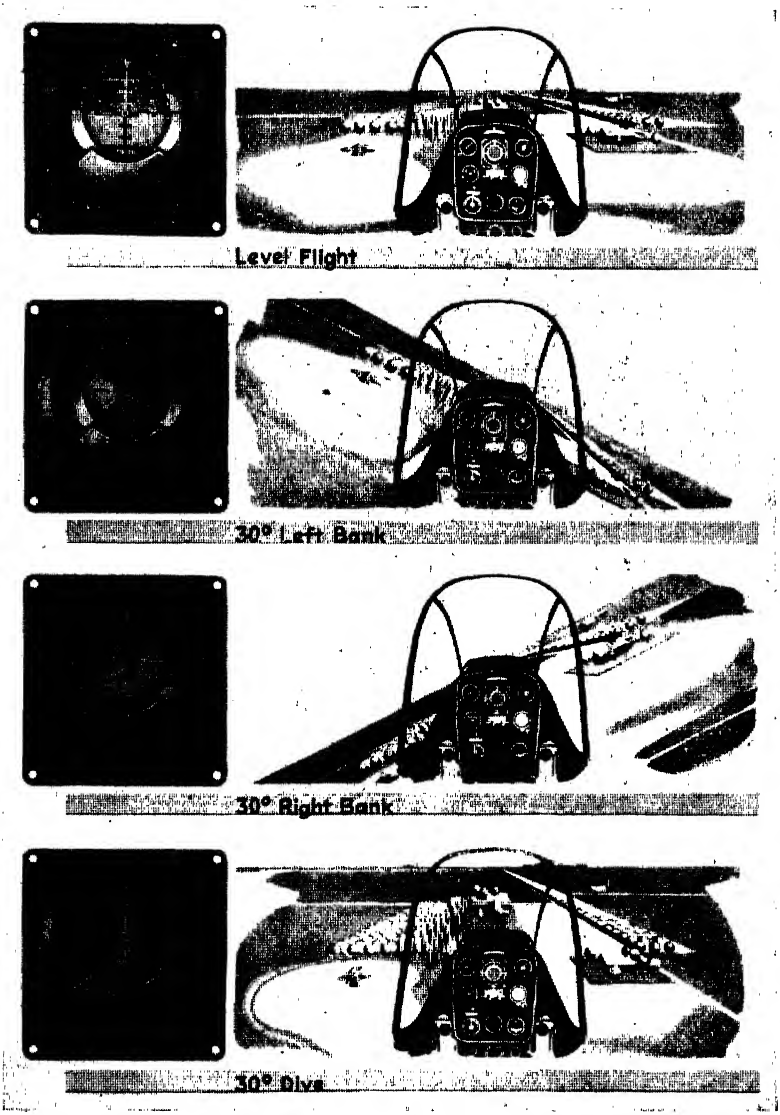


FIG. 265. Attitude gyro indications. (*Sperry Gyroscope Company.*)

and the indicating mechanism shows the *direction* in which the airplane is headed with respect to the direction of the spindle. By means of a setting mechanism, the dial can be set to the points of the compass, and the instrument acts as a compass, with the advantage that it is not subject to the annoying oscillations of a magnetic compass. Without correction, the direction of the spindle will tend slowly to change, chiefly on account of swivel friction. This change can be corrected by resetting the dial by hand, to agree with the magnetic compass, in straight and level flight.

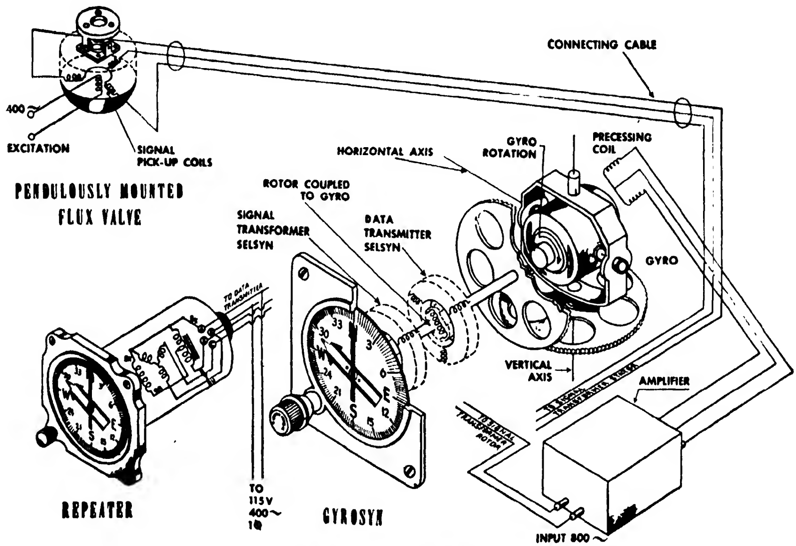


FIG. 266. Gyrocompass elements, general arrangement. (*Sperry Gyroscope Company.*)

When a directional-gyro spindle is automatically corrected to magnetic north by means of an element responsive to the earth's magnetic field, it is called a *gyrocompass.*[1]

The general arrangement of one type of gyrocompass is shown in Fig. 266.

An electromagnetic device sometimes called a *flux valve* is located at a wing tip, tail tip, or other place remote from the magnetic influence of engines, generators, etc. This device contains three coils whose axes are set at angles of 120° to each other, in a horizontal plane. This element detects the direction of the earth's magnetic field with respect

[1] The heavy gyrocompasses used for ships are corrected to true north by means of the influence of the earth's rotation. Such correction is not practicable for the lightweight gyros used in aircraft.

to these coils and translates it into an electric signal. This signal is amplified and used to correct the spindle direction so as to hold it at magnetic north. The gyrocompass is not only free from the fluctuations of a magnetic compass, but it is likely to be more accurate because of the favorable position of the flux valve as compared to the position of a magnetic compass, which must be in the cockpit and hence close to other equipment which may influence its reading.

Gyroscopic Rate Instruments. When a gyroscope is used to indicate a rate of change of angular position, instead of being freely mounted its

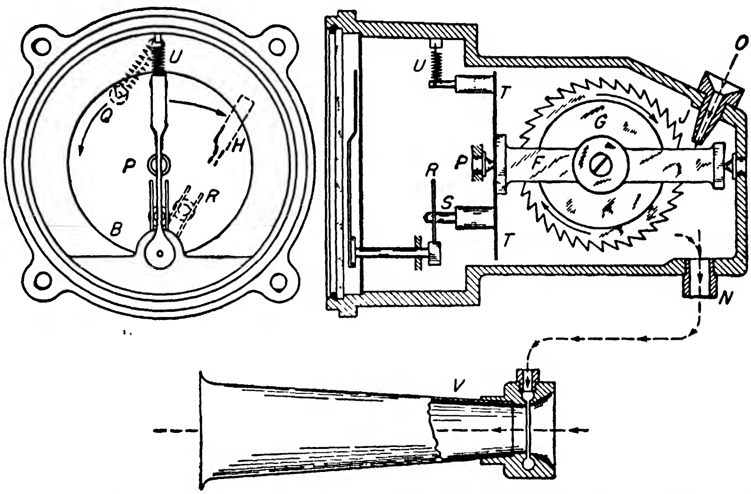


Fig. 267. Mechanism of turn indicator. (*Pioneer Instrument Divison, Bendix Aviation Corporation.*)

motion must be restrained by springs. In this case the *torque* with which the gyro resists a change in spindle direction is measured by the instrument.

Turn Indicator. (Fig. 267.) The principal use for a *rate* gyro is in the so-called *turn indicator*. If the spindle of a gyro is forced to change its direction by means of an applied *torque*, it will exert an equal torque around an axis lying in the plane of the spindle but at right angles to the axis of the applied torque. (A torque is defined as a force acting at a given radius from an axis, in such a manner as to create a turning effort around that axis. Torque is measured in units of force times radius, pound-feet, for example.) Both the applied torque and the resulting torque will be proportional to the *rate* at which the gyro axis is turned. For rate instruments the gyro frame need be pivoted about only one axis. As shown in Fig. 267, in a turn indicator the spindle is parallel to

the lateral or y axis of the airplane, and the frame is pivoted about the longitudinal or x axis. Motion of the gyro frame about the pivot axis is restrained by one or more springs. When the airplane turns around its vertical or z axis, a torque is applied through the spindle bearings which causes an equal torque to be applied around the pivot axis. This torque causes the springs to stretch and allows the gyro frame to turn about the pivot axis through an angle which is proportional to the torque and therefore proportional to the *rate* of turn. The resultant small motion of the gyro frame about the pivot axis is communicated

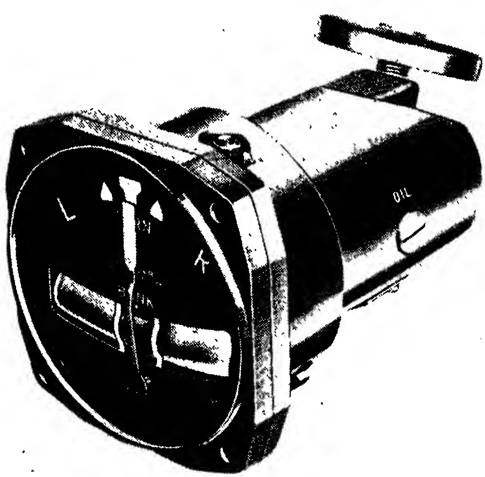


FIG. 268. Bank-and-turn indicator. (*Eclipse-Pioneer Division, Bendix Aviation Corporation.*)

to a pointer which moves over a rate-of-turn scale. It should be noted that motion of the airplane in "roll" (about the x axis) will cause a torque about the z axis, which will not move the instrument about its pivots.

The *turn indicator* is useful in blind-flying operations, since it is very sensitive and indicates turning more quickly than a directional gyro. The magnetic compass is useless as a turn indicator, since in anything but very slow turns it oscillates badly.

The turn indicator is usually combined with a nongyroscopic instrument called a *bank indicator*. This instrument operates on the principle of a pendulum. A common type, shown in Fig. 268, employs a tube, curved downward in the middle, and containing a small metal ball, free to roll along the tube. To *damp* the motion of the ball, the tube is filled with a liquid. When the airplane is on an even keel, the

ball is in the center of the tube as long as the airplane is not turning. But in a turn it is affected by centrifugal force as well as by the force of gravity. If the airplane is banked at the proper angle during a turn, the ball of the inclinometer will remain in the center of the tube. It is thus of considerable aid in making a correct turn, and this is the reason why it is called a *bank indicator.* Obviously it cannot be relied on to indicate whether or not the wings are level. As shown in Fig. 268, the bank indicator is usually mounted just below the turn indicator and on the same instrument face. The combination is called a *bank-and-turn indicator.*

Gyroscope Drive. The gyroscope of Fig. 264 is driven by a small electric motor built into the flywheel of the gyroscope. Current is supplied through *brushes* and *slip rings* mounted at the pivot points. An alternative form of drive is by an air jet, as illustrated in Fig. 267. In this case, the gyroscope wheel is equipped with notches on its periphery, against which a jet of air is directed in order to keep it rotating at high speed. The air jet is created by suction on the instrument casing furnished by an engine-driven pump or by a *venturi* in the air stream, as illustrated, or by both methods together. The venturi alone is now out of favor on account of the danger of clogging by ice or snow in bad weather, *i.e.*, just when such an instrument is needed most.

Automatic pilot is the name given to a gyroscopic device for piloting the airplane on a fixed course. The object of such a device is to relieve the pilot of the strain and monotony of holding a given course for long periods of time, to ensure a minimum of deviation from the course, and to facilitate the maintaining of course and equilibrium under conditions of poor visibility.

The master controlling element of all automatic pilots consists of an attitude gyro and a directional gyro or gyrocompass. The indications of these instruments are transmitted to *servomotors,* which move the control surfaces in such a way as to maintain the condition of flight for which the instrument is set by the pilot. Modern automatic pilots can be set to hold a straight and level course in a given direction, to hold a controlled climb or glide, and in some cases even to hold a uniform rate of turn or to follow a radio beam.

Automatic pilots may operate electrically or by means of air and hydraulic systems. Figure 269 shows the components of an electric automatic pilot and their typical locations in a large airplane. The basic controlling elements are a vertical or attitude gyro and a gyrocompass. These two instruments, instead of furnishing dial readings, are arranged so as to furnish electric signals which indicate the devia-

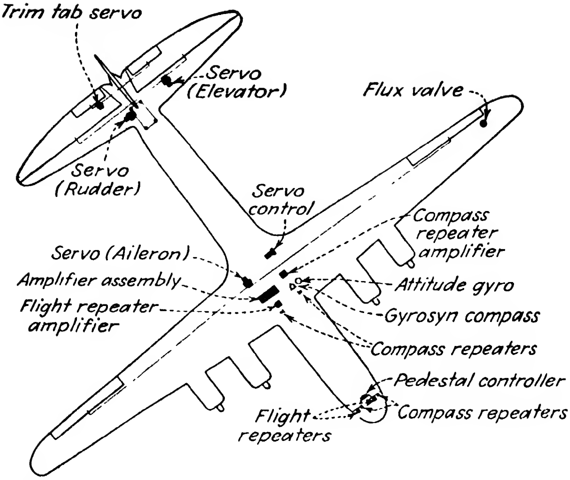


FIG. 269. Components of an automatic pilot of the electric type. (*Sperry Gyroscope Company.*)

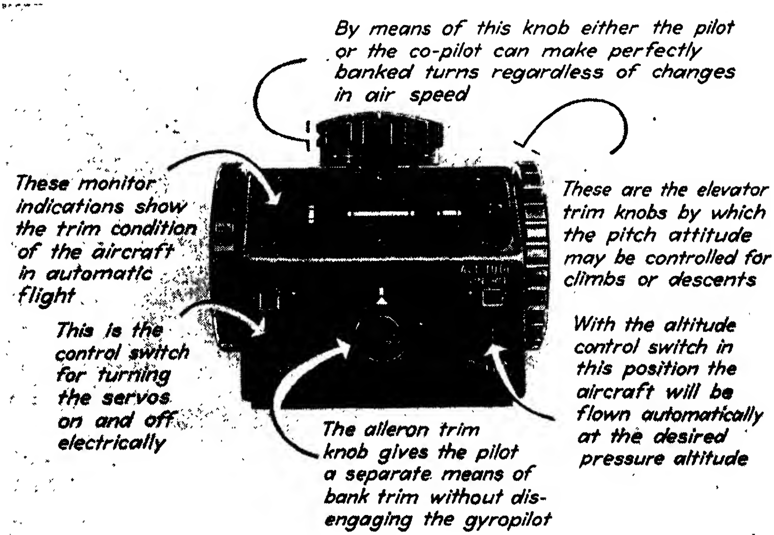


FIG. 270. Master controller of an automatic pilot of the electric type. (*Sperry Gyroscope Company.*)

tion of the airplane's position and direction from the course set by means of the master control unit (Fig. 270). The signals from the gyros are fed into an electronic amplifier, which in turn controls the supply of electricity to the servomotors (Fig. 271). Attitude of the airplane and its heading are indicated by means of *repeaters*, or instruments with faces like those of the attitude gyro and gyrocompass previously described. These repeaters are operated through an amplifier

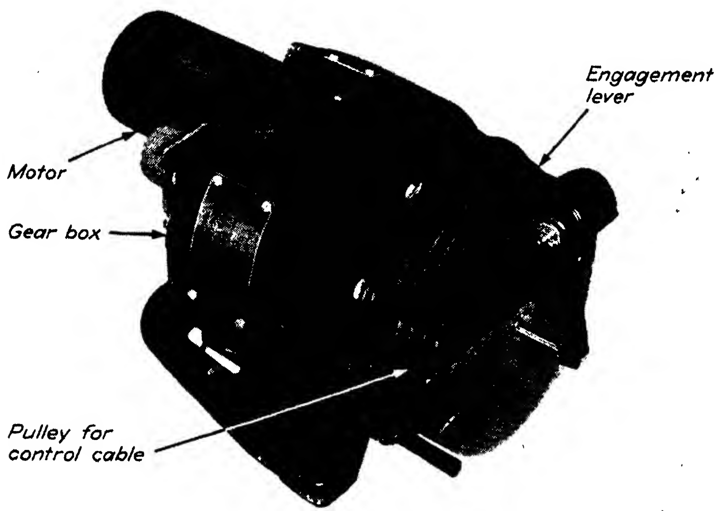


FIG. 271. Servomotor for electric automatic pilot. (*Sperry Gyroscope Company.*)

by means of electric signals sent out by the attitude gyro and gyro compass.

When automatic piloting is desired, the operator sets the master controller to a given attitude (climb, glide, or level flight) and to the desired course, and switches on the automatic pilot. The gyros then start signaling the *differences* between the set course and attitude and the airplane's actual course and attitude. These signals operate the servomotors and the control surfaces to bring the airplane into agreement with the control setting. Thereafter, as small deviations occur between the setting and what the airplane is doing, the servomotors operate the controls to bring the airplane back to the set attitude and course.

The automatic pilot illustrated in the figures also has means for setting for a controlled turn (top knob, Fig. 270) and can be supplied with

means for connecting the control mechanism to a directional radio receiver in such a way that the airplane will follow a radio beam.

Another form of automatic pilot (Ref. I-3) operates with hydraulic cylinders as servomotors. The hydraulic pressure to the cylinders is controlled by an air-pressure system controlled by the gyros. The gyros are air-operated. This system is less expensive and less versatile than the electric system.

SYSTEMS FOR REMOTE INDICATION

In large airplanes, the problem of transmitting instrument indications over considerable distances becomes a serious one. Several systems, all of them electrical, have been developed to meet this problem. The general principle of operation is to translate the basic signal into an electrical indication, which is then delivered through wires to an indicator, which translates the electrical indication into the position of a pointer on a dial. By the use of such systems, the only connection required between the source of the signal and the indicator is a lead containing a few small insulated wires.

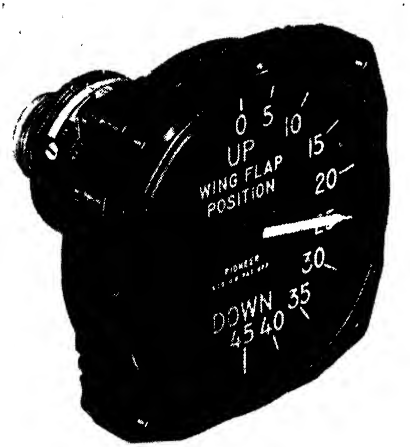


FIG. 272. Wing-flap position indicator, receiver. (*Eclipse-Pioneer Instrument Division, Bendix Aviation Corporation.*)

The instrument which translates the basic signal into electrical terms is called a *transmitter*, and the instrument which translates the electric signal to a pointer position is called a *receiver*. Both instruments resemble small a-c electric motors and are supplied with alternating current from the airplane's electric system. These instruments are wired so that the rotation of the shaft of one is followed exactly by a similar rotation of the shaft of the other. In other words, the angular position of the shaft of the transmitter is duplicated by a similar angular position of the shaft of the receiver. In use, the transmitter shaft is attached to the mechanism whose position is to be transmitted. This may be the position of the shaft of a fuel-level gage (Fig. 253), a fuel flowmeter (Fig. 254), a gyroscope pivot (Fig. 266), a landing-gear or flap control mechanism (Fig. 272), or any other mechanical position which

it is desired to transmit over a considerable distance. The suffix "syn-" has generally been used to indicate that an instrument incorporates this remote-reading feature (see Figs. 266 and 269).

Accelerometer. This is a flight instrument which indicates the acceleration force due to airplane maneuvers. Its use is confined to military fighters and to experimental or training installations. A weight is mounted on stiff springs in such a way that a small vertical motion of the weight moves a pointer on a scale marked in gravitational or g units, *i.e.*, in multiples of the earth's gravitational pull. The vertical displacement of the weight is proportional to the vertical, or z-axis, acceleration of the airplane. The chief object of such an instrument is to enable the pilot to avoid accelerations which might cause failure of the wing structure.

NAVIGATING INSTRUMENTS

Navigating instruments may include a direction indicator, or *compass;* a *sextant,* for determining the airplane's location on the earth's surface; a *drift indicator,* to determine the sideward drift of the airplane due to a cross wind; and a clock or *chronometer,* to determine the time of day.

The gyrocompass, in which the earth's magnetic field is used to set a directional gyro, has already been described. This instrument is too elaborate for small airplanes, which use a magnetic compass operating on the familiar principle of a ship's compass or pocket compass. All airplanes carry at least one magnetic compass. The airplane compass must be small, and light compared to a ship's compass. Like the latter, it must be *damped* by submerging the swinging magnet assembly in a bath of liquid.

Figure 273 shows an ordinary airplane compass. Since in airplanes it is not convenient to mount the compass so as to look down on a horizontal dial, the compass is arranged so that the observer looks at the rear edge of the dial. This point of view is very convenient for mounting purposes, but is likely to be confusing to the observer because of the fact that the "north" mark on the dial is actually on its south edge, and when the airplane turns to the right, the dial appears to move in the same direction. To obviate this difficulty, one company has developed a compass (Fig. 274) in which the necessarily horizontal magnet assembly is geared to a vertical dial. This compass has a *course-indicating* marker, which can be set to the desired course by means of a hand-operated knob.

All compasses are equipped with compensating magnets, which are

stationary in the casing, but whose position can be adjusted to cancel out the magnetic influence of engines, electrical equipment, etc. Without compensation there would be serious errors in the compass readings.

Sextant. The location of the airplane on the earth's surface is usually expressed in latitude and longitude, and is determined with the aid of a *sextant,* which is an instrument for measuring the angle between the horizontal and the sun. The sextant is familiar in marine navigation. The only difference between its use in the airplane and in the ocean-going vessel is that in the case of the airplane it is seldom possible to

FIG. 273. Airplane magnetic compass. (*Eclipse-Pioneer Division, Bendix Aviation Corporation.*)

use the horizon to establish the horizontal position of the instrument, and therefore a level is necessary from which to measure the angle. The airplane sextant must be very light and compact and very easy to operate, since time and space are usually much more limited in the case of the airplane than in the case of the ocean-going vessel.

Drift Indicator. An instrument of some importance for aerial navigation is the *drift indicator,* which is used for the purpose of determining the *drift* or sideways motion of the airplane due to the wind. In making a long flight, it is desirable that drift be determined and corrected for; otherwise the airplane will not be following a straight course to its objective. Drift indicators operate by looking at an object on the ground or in the water through a circular screen on which one or more straight lines are marked. The screen is rotated until the reference lines are parallel to the apparent path of objects on the ground. A correction angle for the compass course is then indicated on the dial of the instrument.

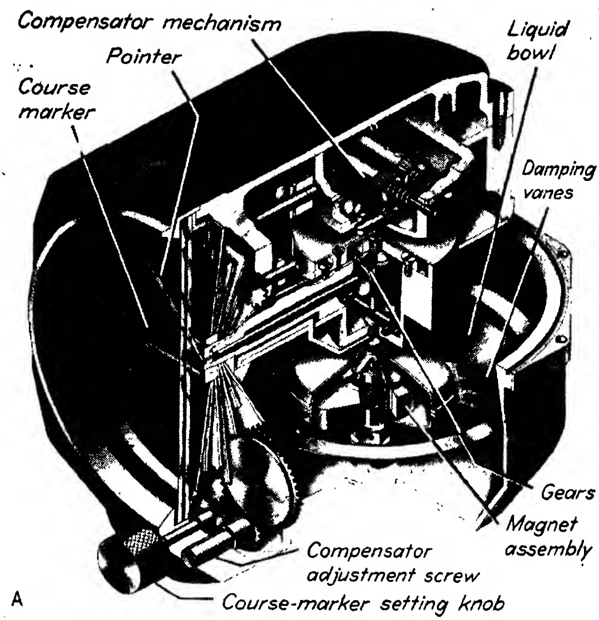


FIG. 274. Compass with vertical dial (Kollsman direction indicator). (a) Cutaway view, (b) face. (*Kollsman Instrument Division, Square D Company.*)

Clock. For navigating purposes it is necessary to carry a clock, or *chronometer*. The chronometer is a kind of clock having mechanism of especial accuracy. Time, as indicated by the clock, or chronometer, is used in computations of latitude and longitude and of total distance traveled. For certain purposes it is convenient to have a *stop clock* combined with the usual form. This is simply an extra hand, usually a "second hand," so arranged as to be stopped and started by pushing a button, as in the case of a stop watch.

RADIO EQUIPMENT

The radio is now a most important adjunct to the navigation of airplanes and is indispensable to reliable air transportation (see Ref. I-7). It is used in three ways: first, to obtain general information from ship and ground stations as to location, time, weather, etc.; second, for the direct determination of the course and position of an airplane by means of directional sending or receiving systems; and third, to operate the airplane directly by means of a connection between radio signals and the automatic pilot.

Apparatus for general communication by radio is quite similar to the portable type of apparatus used on the ground, since both are built to be as light and as compact as possible. Both the telephone and the telegraph systems are used, although the greater convenience and speed of telephone communication, together with the fact that no telegraphic code training is required for its use, have made it by far the more popular type.

Much of the radio equipment used on small airplanes comprises merely a receiving set in the airplane, giving *one-way communication* only. The limitations of this are obvious, but even a one-way set may be of inestimable assistance in flying operations, particularly under conditions of bad weather or poor visibility.

Figures 275 and 276 show typical airplane radio sets for receiving and sending. Receiving sets are considerably more elaborate than ordinary household sets, in order that they shall be very reliable and shall cover the different wave bands necessary for receiving beacon signals, weather reports, broadcasts, etc. The sets illustrated are of considerable range and are designed for use in large transport airplanes. Where the receiver and transmitter cannot be mounted directly in front of the operator, a remote-control panel (Fig. 275) is used. This panel is mounted at the operator's station and connected to the main equipment by wires and flexible shafting. The *dynamotor* shown in Fig. 275

is used to convert the current supplied in the airplane to a suitable voltage and frequency for the radio equipment.

Radio Compass. By the use of a "loop" receiving antenna on the airplane, the direction of any radio sending station can be determined

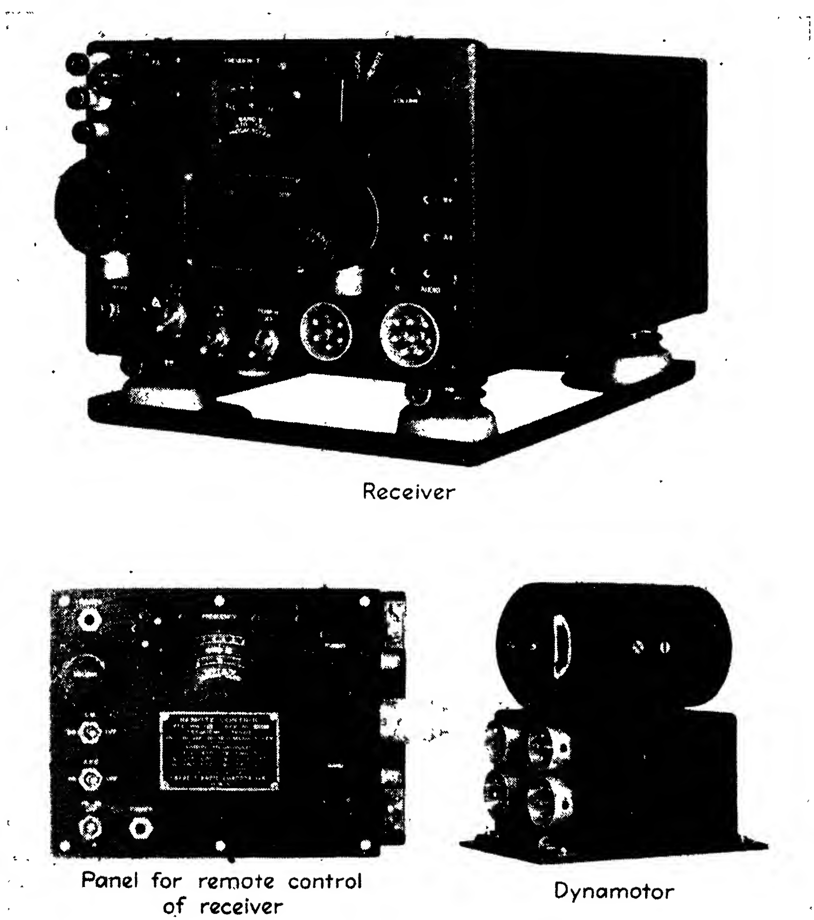


FIG. 275. Airplane radio receiver and auxiliary equipment. (*Bendix Radio Division, Bendix Aviation Corporation.*)

if the signals can be heard. One such system is illustrated diagrammatically by Fig. 277. This system is so arranged that the bearing of the radio station to which the instrument is tuned is indicated on a dial. The *bearing* is defined as the direction of the station with respect to the heading of the airplane. The compass works on the principle that

when the plane of the loop antenna points directly at a sending station, the signal disappears. In a simple radio installation the loop is rotated to the null position by hand, and the station bearing is indicated by the loop direction. In the more elaborate type illustrated by Fig. 277, the loop is automatically rotated to the null position by an electric motor,

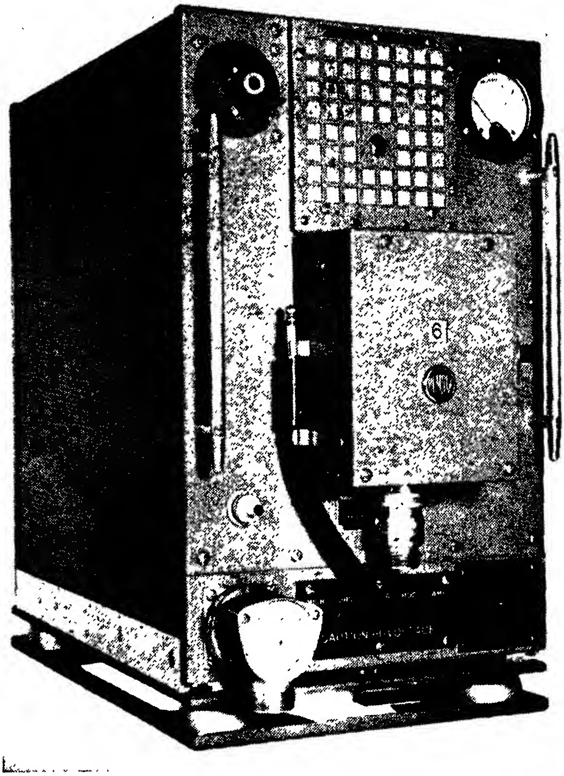


FIG. 276. Airplane radio transmitter. (*Bendix Radio Division, Bendix Aviation Corporation.*)

and the bearing of the loop is indicated on remote dials, controlled electrically. The readings of a gyrocompass can be combined on the same dial with those of a radio compass.

RADIO BEACONS

Radio sending stations designed for the specific purpose of indicating a given *course* to aircraft are known as *radio beacons*. They may be logically divided into two classes: *route beacons*, used over considerable

distances to indicate a fixed course or route, and *local beacons*, used over short distances for the purpose of assisting the airplane pilot in locating a landing field, and even in making the actual landing. Both types are, of course, of especial utility under conditions of poor visibility, but the *route beacon* may also be of great assistance in good weather when flying over water or over land routes whose ground marking is inadequate.

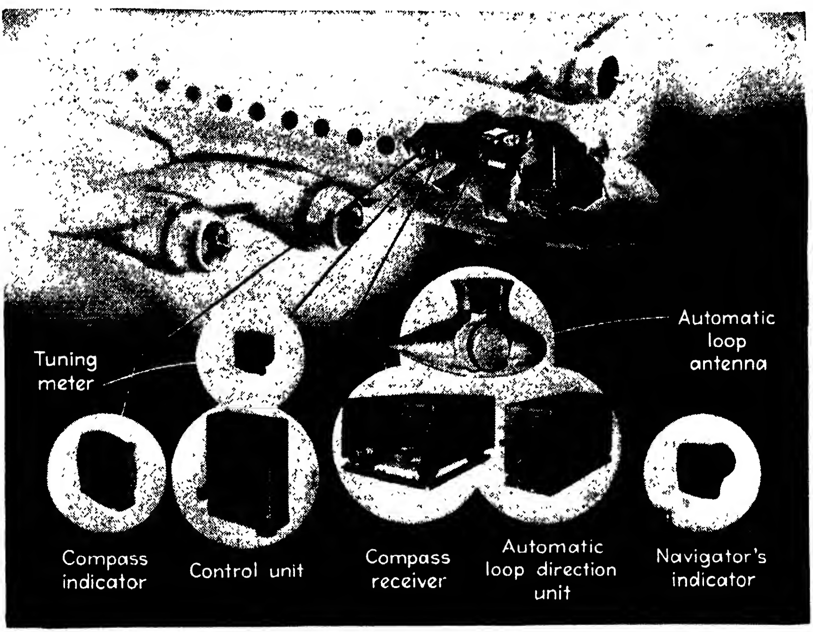


FIG. 277. Radio compass (components in plane). (*Bendix Radio Division, Bendix Aviation Corporation.*)

Both types of beacons depend for their operation on the remarkable characteristic of radio signals, whereby they can be *directed*, or sent out so as to be especially strong in certain predetermined directions. These signals must be sent from stations on the ground whose location is known by the pilot, and they are useful chiefly when the aircraft is flying directly toward or away from the sending station. The most usual application is where the sending station is located at or near the destination of the airplane. The principles of operation are essentially the same for all types of radio beacon, but individual installations may differ considerably in such details as the electrical characteristics of the signals sent out and the type of indicator used in the airplane.

Sending antennas for route beacons usually consist of two loops set at an angle to each other. The signal strength sent out by such antennas forms a pattern in a horizontal plane, such as the one indicated in Fig. 278. This is called a four-course beacon, the *courses* being the strips where the strength of the signals from both loops is equal. Modifications in the loop system are possible so as to give a larger or smaller number of courses, if so desired. The signals sent from the two loops must be of exactly the same wave length. The type of signal sent usually consists of a continuously repeated dot-and-dash letter from each

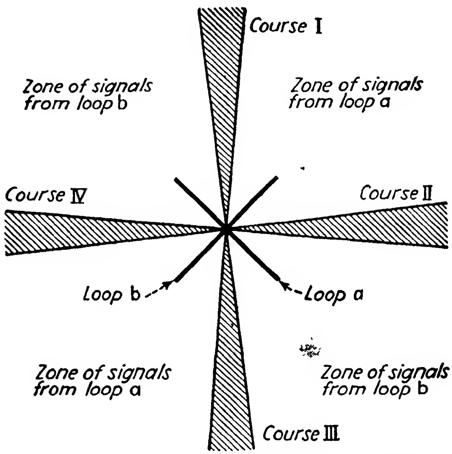


FIG. 278. Signal pattern for four-course radio beacon. Shaded areas indicate zones where signal strength from both loops is the same.

loop, with the "call" of the station inserted at frequent intervals for identification. The letter sent out by one loop "interlocks" with that sent out from the other in such a manner that when both are heard with equal intensity the dots and dashes of one fill the spaces of the other, and a continuous buzz results; thus:

Antenna *a*: ——— — ——— — ——— — ———
Antenna *b*: — ——— — ——— — ———
Combination: ————————————————————————

When the antenna of the receiving airplane is in one of the *beams*, or zones of equal signal strength, the two signals will be heard with equal intensity and the resulting sound in the earphones will be a continuous hum. When, however, the airplane drifts out of the beam, one signal is heard above the other, and the pilot knows in which direction to correct his course by noting which of the two signals is louder.

Local beacons may be quite similar to the route beacon just described, except for a much shorter range, or they may be short-wave beacons having a special shape of beam. In either case, the beam of the local beacon usually crosses the beam of a route beacon at a point near the airport, so that the local beacon may be "picked up" by an airplane flying along a given route.

Short-wave local beacons may be given special shapes of beam on account of the peculiar characteristics of short-wave radio signals, which allow them to be accurately reflected or directed by special types

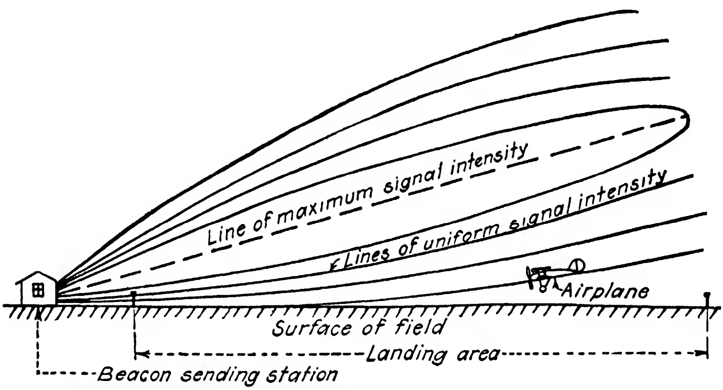


FIG. 279. Vertical section of signal pattern of short-wave local beacon for landing purposes. Airplane follows a line of uniform signal strength.

of antennas into *intensity patterns* or *signal-strength patterns* of various definite shapes. A type of short-wave local beacon now being installed at large airports has a station, located near the airport, sending out a signal along a beam controlled to a definite shape, as shown in Fig. 279. This beam is directed to the path along which the airplane should glide in to land. To use this beam, the airplane receiving set must be equipped with an instrument to indicate the intensity of the signal, which thus enables the pilot to follow a line of uniform signal intensity along the beam.

Blind-landing Systems. By combining two beam patterns at right angles to each other, a flight path can be indicated both in the horizontal and vertical planes. Blind-landing systems using this principle usually mount the beam-sending equipment on trucks so that it can be moved around to serve any particular runway, as indicated by Fig. 280. In the system illustrated, one set sends out a *localizer* beam for directing the airplane in the general direction of the runway while it is still some distance off. Another set accurately indicates the final *glide path*

to be followed to bring the airplane into contact with the runway at the proper point. The beams are followed either by reference to an indi-

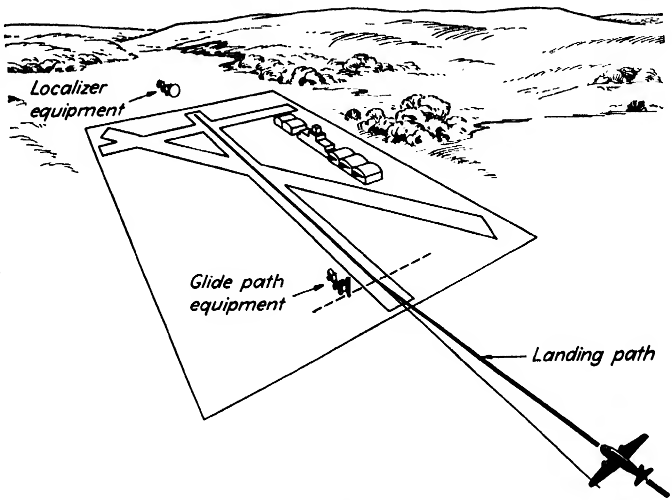


FIG. 280. Glide path indicated by radio beams from truck-mounted short-wave stations. (*Sperry Gyroscope Company.*)

cator (Fig. 281), or by electrical connection of the beam receiver to the automatic-pilot controller. The beam indicator has two pointers, one of which indicates vertical deviation and one horizontal deviation, from the glide-path beam. References I-4 and I-7 give more complete details of this system. Systems of this kind are classed as ICS, or instrument-control systems.

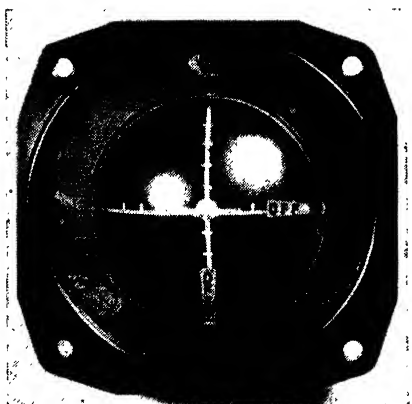


FIG. 281. Flight-path indicator. Pointer shown in "on-course" position. (*Sperry Gyroscope Company.*)

Radar. A blind-landing system entirely different from that just described is called the *ground-control approach* or GCA system (Ref. I-5). In this system the airplane is observed from the ground by means of *radar*, and the pilot is directed along the glide path (or "talked down," as it is called) by radioed instructions given through his ordinary radio-telephone equipment.

As is now popularly known, radar operates by sending out very high frequency radio waves, which are reflected back from any object which they strike. This principle is used in radar to furnish an image on a fluorescent screen of objects at which the equipment is "aimed." Radar is thus, quite literally, a system for seeing through fog and darkness.

In the GCA system, the radar equipment is usually mounted on a truck so that it can be moved to any runway of the airport. One radar set observes the airplane as it approaches the field and another is arranged to "look" along the correct glide path. This latter set is used in the final approach to keep the airplane in the center of the glide path by giving the pilot proper verbal instructions. The GCA system appears to be a very promising solution of the problem of landing under conditions of little or no visibility.

TYPICAL INSTRUMENT INSTALLATIONS

It is seldom that all the instruments previously described are used together on the same airplane. For the ordinary airplane, engaged in "contact" flying, *i.e.*, flying by reference to the ground in clear weather, many of the navigating and flying instruments are not necessary. For very long flights, on the other hand, even more instruments, and more elaborate ones than those described, may be used.

The instruments usually required in an airplane used for contact flights are: the engine tachometer, oil-pressure gage, water or oil thermometer, gasoline-level gage, altimeter, air-speed indicator, and compass. Airplanes fully equipped for blind flying (not blind landing) carry, in addition to the above, an attitude gyro, a directional gyro, rate-of-climb indicator, turn-and-bank indicator, and clock.[1] Two-way radio-communication apparatus is almost universally used in this class of airplane, and radio-directional equipment is also in general use. For air-line and military operations, very elaborate instrumental equipment is carried, especially on multi-engine airplanes. Navigating instruments other than the radio, compass, and clock are required for special or for long-distance flights only.

ELECTRIC-POWER SUPPLY

Generators. The electric power for radio, lighting systems, etc., is usually supplied by a generator (Fig. 282) driven from the engine, and used in conjunction with a storage battery. The airplane generator is

[1] It is possible to do a limited amount of blind flying by adding only the turn-and-bank indicator to the first list of instruments.

quite similar to the electric generators used on automobiles, except that it is made as light as possible for its capacity. It is fitted with a splined shaft to fit a corresponding drive shaft which must be provided on the engine. A pad with bolts serves to fasten the generator in place. Since engine-driven generators do not run at constant speed, they are equipped with an automatic electrical device, known as a *voltage regulator* which keeps the output voltage approximately constant, in spite

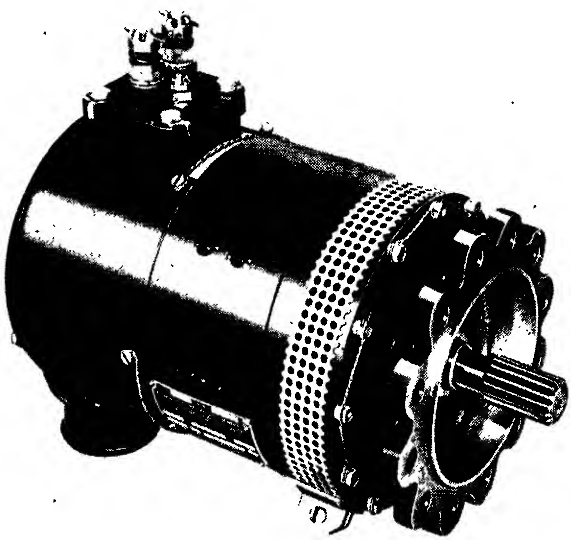


FIG. 282. Engine-driven generator. (*Eclipse-Pioneer Division, Bendix Aviation Corporation.*)

of speed variations. Because of the necessity of using storage batteries, the basic supply is usually low-voltage direct current. This is converted to alternating current for radio and instrument use by means of small rotary convertors called dynamotors, such as that shown in Fig. 275.

LIGHTING SYSTEMS

An airplane that flies at night must be equipped with a lighting system which includes lights for illuminating the cabin and the instruments and also the required *running lights*. In most cases, flares for illuminating the ground in order to make an emergency landing are also carried.

Interior Lighting. Small electric bulbs are used to illuminate the instrument board, although very often the instruments are also

equipped with self-luminous dials and pointers for use in case of failure of the lights. In closed-cabin passenger airplanes, lights for the cabin are usually fitted.

Running Lights. The lights which an airplane displays to indicate its position and course to other airplanes and to observers on the ground are required by law in most countries. In the United States, every airplane must display at night a small red light near the left wing tip, visible from the front and left side of the airplane. A green light visible from front and right side must be carried on the right wing tip, and a white light visible from behind must be carried near the tail. For transport aircraft, these lights are of the flashing type.

Landing Lights. Most airports which are used at night are equipped with a system of lighting, so that the field can be illuminated to assist an airplane in landing. In addition, airplanes for night flying carry *landing lights*. These usually take the form of powerful electric headlights, located in the leading edge of the wings or on the "nose" of the fuselage. These lights are arranged to shine forward and downward and may be turned on by the pilot. For emergency night landings, *parachute flares* are carried. A parachute flare consists of a small parachute, to which is attached a magnesium flare, the whole being contained in a metal tube. Flares are arranged in the airplane so that they can be discharged one by one. When a flare is discharged, it is automatically ignited and burns while it descends, assisting the pilot to effect a landing on any suitable field which comes within the range of the flare.

HYDRAULIC SYSTEMS

Many airplanes use *hydraulic* power rather than electric power to operate landing gear, control surfaces, etc. Oil under pressure supplies the motive force in such systems. The pressure is created by means of engine-driven pumps which supply the oil against air pressure in a thick-walled reservoir or *accumulator*. The parts to be moved are equipped with hydraulic *cylinders*, which carry *pistons* against which the oil pressure works. The pistons are packed with rubber rings or leather cups, as in a bicycle pump, and are connected to the accumulator by means of high-pressure metal tubing. Control valves admit the oil to the cylinders, or release it from them, as required. Electric power is now favored over hydraulic power for most airplanes.

DE-ICERS

Under certain weather conditions, moisture from the atmosphere tends to collect and freeze on various parts of an airplane. Ice forma-

tion of this kind is very dangerous, as it may seriously interfere with performance and controllability or increase the weight so that a "forced" landing is necessary. Thus airplanes which are to be operated in all kinds of weather must carry *de-icing* equipment.

The most usual type of wing de-icer (Fig. 283) consists of strips of sheet rubber carried along the leading edge. The sheets are fastened to the wing along their edges. When ice begins to form, air from a small pump is intermittently blown into and let out of the space under the rubber sheets. This causes the rubber to bulge and crack off the ice.

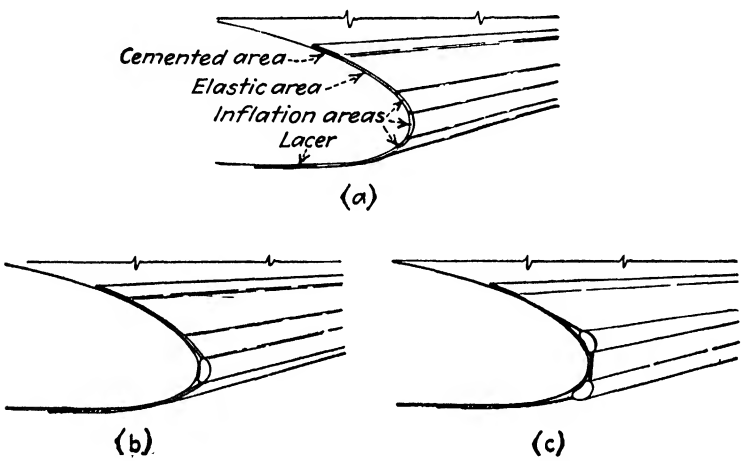


FIG. 283. De-icer, inflatable rubber type, on the leading edge of an airplane wing. (*a*) Normal position, (*b*) center strip inflated, (*c*) upper and lower strips inflated. (*Eclipse-Pioneer Division, Bendix Aviation Corporation.*)

As most of the ice on wings collects along the leading edge, this prevents the wings from accumulating a dangerous amount, except under very severe conditions. This equipment is rather elaborate, requiring not only the rubber strips on wings and control surfaces, but also an engine-driven pump, pressure regulator, control valve, and piping.

Propeller de-icers usually consist of a system of supplying a de-icing fluid, such as glycerin or oil, to a duct in the leading edge of each propeller blade. Holes in the duct distribute the fluid over the blade. A simpler system supplies fluid to the base of each blade and depends on centrifugal force and airflow to spread it over the blade surface.

Recently, systems of thermal de-icing (see Ref. I-6) have begun to be favored over those previously described. In such systems, passages in the wing and control-surface leading edges are supplied with air heated by the engine exhaust. Such systems cannot be added to an existing

airplane, but must be originally built in. Thermal de-icing of propeller blades is usually by electric heating.

PARACHUTES

As is now well known, the parachute consists of an umbrella-shaped piece of cloth of very light weight and very great strength, usually

FIG. 284. Parachute pack. (*Irving Air Chute Company, Inc.*)

about 25 ft in diameter. Silk and cotton were formerly used, but now the most popular material is *nylon*. Attached around the edge of the parachute are a large number of cords which run to the *harness* worn around the body. When not in use, the parachute is carried in a cloth bag, usually strapped to the wearer. Figure 284 shows a parachute "pack" of this kind. In order to use the parachute, the wearer must first jump out of the airplane, and must be careful not to open the parachute until he has fallen clear of all parts of the machine. He then pulls a ring which opens the pack and allows the parachute to drop out,

the parachute being opened by the rush of air through its folds. In dropping troops and supplies in military operations, the *rip cord* is attached to a length of rope fastened in the airplane. When the parachute falls to the end of this rope, it is pulled open automatically.

Most parachutes carry a small *pilot* parachute to assist in opening the main parachute. The pilot parachute is attached to the center of the main parachute and opens first, pulling the main parachute into the proper position for opening. The stability of a parachute depends on

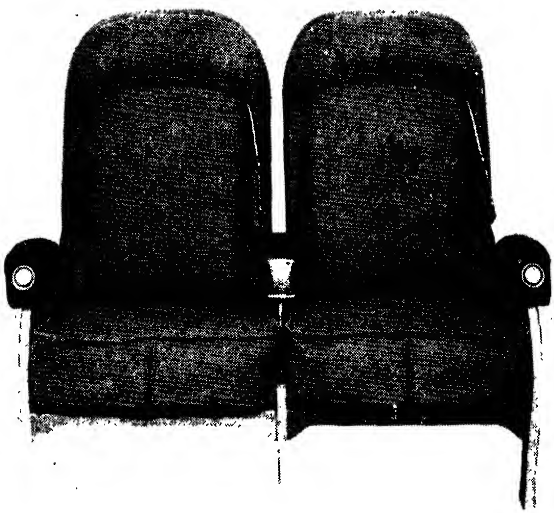


FIG. 285. Seat-type parachutes. (*Irving Air Chute Company, Inc.*)

its shape or on its *venting*, or on both. Some parachutes are equipped with one or more openings or *vents* which allow air to escape slowly. This seems to assist greatly in preventing a swinging motion during descent. Another type uses no vents, but resembles in shape the head of a mushroom, having rather a flat top with its greatest diameter considerably above the mouth.

Seat Parachutes. Recently parachutes have been developed to be incorporated into airplane seats (Fig 285). The straps are concealed by flaps in front of the seat cushion and at the sides of the back cushion. The harness can be quickly attached by pulling these straps across the body and fastening them by snap hooks.

Use of Parachute. Parachutes are required in the military and naval services in this and many other countries. The hazards of military flying are considerably greater than those of commercial flying,

and for this reason the use of the parachute in military airplanes is much more common than in commercial airplanes. In airplanes carrying a large number of passengers, it would take considerable time for the passengers to get out through the small doors available, and therefore in most accidents to commercial planes parachutes would be useless. For these reasons, the use of the parachute in commercial operations is not very general. Figure 286 shows a parachute in use.

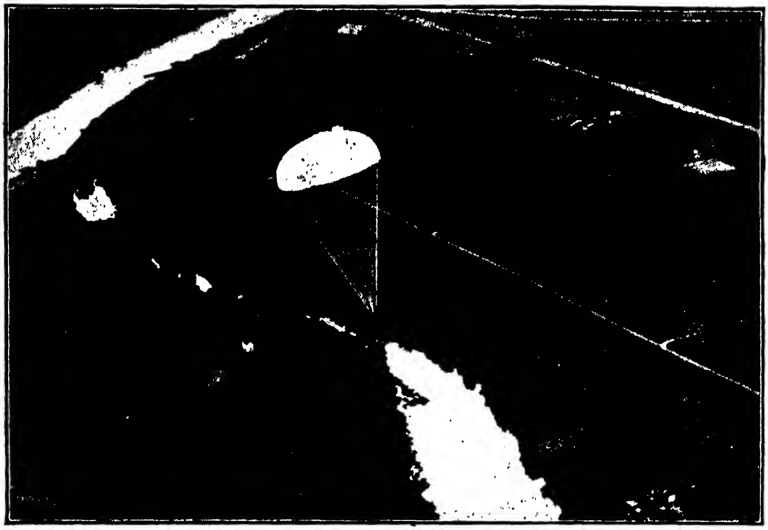


FIG. 286. Parachute in flight. (*Materiel Division, U.S. Army Air Corps.*)

MISCELLANEOUS EQUIPMENT

A **safety belt** is provided for each pilot and passenger. It consists of a heavy belt attached to the structure and so arranged that it holds the occupant in the seat until the buckle is released. It is important that a quick-release buckle be used on such a belt, so that the occupant can get out quickly in an emergency.

For high-altitude flights, or flights of long duration in cold weather, special clothing is necessary. This is usually fur-lined, and in some cases electrically heated. A supply of oxygen is also necessary for flights at very high altitude. This oxygen is usually contained in small steel flasks under very high pressure. By means of an automatic valve, the oxygen is released very slowly to a mask over the pilot's face and is breathed through a tube held in the mouth.

Equipment for passenger comfort has been highly developed by the civil air lines. Comfortable adjustable seats of good design are in gen-

eral use. Sleeping berths, toilet facilities, etc., are similar to those used in Pullman cars, but, of course, much lighter in weight. Heating and ventilation facilities are, in general, reasonably satisfactory.

NOISE PREVENTION

In connection with the improvement of passenger comfort, the question of noise is a serious one. The tremendous noise made by the modern airplane is both disagreeable and fatiguing to the occupants. The chief sources of this noise are engine exhaust, propeller, mechanical parts of the engine, the rush of air past the airplane, and vibration of the airplane structure. Two possible methods of attacking this problem are available, namely, to reduce the noise or so to insulate the cabin that noise from outside does not penetrate to the ears of the passengers.

Mufflers have been developed which will greatly reduce the exhaust noise without adding unreasonably to weight and drag. They are seldom used, however, since so much noise usually remains that the absence of the exhaust noise is hardly noticed.

Reduction of **propeller noise** constitutes a difficult problem, although the use of large, very slow-turning propellers would go a long way toward its solution.

As yet, the problem of **mechanical noise** in the engine has not been attacked, but when exhaust and propeller noises have been reduced, its reduction or elimination will be necessary. Probably the same methods which have so successfully reduced automobile engine noise can be applied, with suitable modifications, to the airplane engine.

Sounds due to the rush of air past the airplane have already been greatly reduced by cutting down the number of wires, struts, etc., and by the general improvement in streamlining, which is still in progress. Similarly, vibration of airplane parts is automatically reduced by the process of simplifying and stiffening structural members, which is constantly taking place as airplanes are improved.

In **cabin insulation** against noise, definite progress has been made, and most large passenger airplanes employ effective sound-proofing material in the walls of their cabin structures. The ultimate solution of the noise difficulty will undoubtedly be achieved by a combination of noise reduction and cabin insulation.

Considerable vibration from the engines is still present, even in the best modern passenger planes. Improved engine mountings and possibly improved engine balance are the most promising ways of reducing this vibration. Jet engines and gas turbines have much less

vibration than reciprocating engines and will effect great improvement in this respect.

HIGH-ALTITUDE FLYING

As far as airplane performance is concerned, flying at very high altitudes is already possible. The problem of regular operation at high altitudes, however, centers around that of the physical comfort of the occupants.

Very high altitude military flying, and even moderately high (over 10,000 ft) continuous flying with passengers requires that the cabin be "supercharged," *i.e.*, maintained at higher than atmospheric pressure. Present transport airplanes under development and one or two types already in use are designed to carry a cabin pressure equivalent to that at 8,000 to 10,000 ft above sea level.

The use of a supercharged cabin involves not only a structure capable of withstanding the necessary difference in pressure between cabin and atmosphere, but also the necessary air-pumping, piping, and control equipment. Blowers may be driven by the main engine or by auxiliary engines. Pressure control must be automatic. Since a sudden drop of the cabin pressure to atmospheric pressure at high altitude would have serious consequences, every possible precaution is necessary to prevent this, including reliable pumping equipment, automatic seals on ventilating holes, etc. Airtight glands for all control shafts passing through the cabin walls and strong and airtight doors and windows are also necessary. All these add to the weight of the airplane but appear to be justified, in large transports, by the increased cruising speed which high-altitude operation allows.

The supercharged cabin has not yet been used extensively on military airplanes, which rely chiefly on oxygen and heated clothing to make high-altitude flying possible. An exception to this statement is the B-29 bomber, which has a pressurized interior. The success of this airplane indicates the probability of wider use of pressurized cabins in future military airplanes.

EQUIPMENT FOR STRATOSPHERE FLYING

Popular interest in the possibility of flying in the stratosphere (above 40,000 ft) has been stimulated by statements to the effect that tremendous speeds could be attained by airplanes flying in this region. The chief difficulty in designing airplanes to operate satisfactorily at such altitudes comes from the fact that the cabin, the supercharging equipment, and the equipment necessary for safety and comfort

become increasingly heavy as the operating altitude is increased. At the present time, flying for any extended period above about 35,00 ft has not proved practicable. Whether or not it will be practicable in the future depends on whether it proves possible to build the necessary special equipment within a reasonable weight limit and with the necessary reliability.

APPENDIX

In describing and tabulating airplanes and their engines and propellers in Chaps. X, XIV, XV, and XVI, use of shortened names and abbreviations was convenient. These are listed below:

ENGINES

Allison	Allison Division, General Motors Corporation
Cont	Continental Motors Corporation
Frank	Franklin, Aircooled Motors Corporation
GE	General Electric Company (turbojets)
Lycom	Lycoming Division, Avco Mfg. Corporation
P & W	Pratt and Whitney Aircraft Division of United Aircraft Corporation
Rolls-Royce	Rolls-Royce Merlin, Manufactured by Packard Motor Car Company
West	Westinghouse Electric Corporation (turbojets)
Wright	Wright Aeronautical Corporation, Division of Curtiss-Wright Corporation

AIRPLANE BUILDERS

Aeronca	Aeronca Aircraft Corporation
Beech	Beech Aircraft Company
Boeing	Boeing Airplane Company
Convair	Consolidated Vultee Aircraft Corporation
Curtiss	Curtiss-Wright Corporation, Airplane Division
Douglas	Douglas Aircraft Company, Inc.
Fairchild	Fairchild Aircraft Division of Fairchild Engine & Airplane Corporation
Grumman	Grumman Aircraft Engineering Corporation
Lockheed	Lockheed Aircraft Corporation
McDonnell	McDonnell Aircraft Corporation
Martin	The Glenn L. Martin Company
North American	North American Aviation, Inc.
Northrop	Northrop Aircraft, Inc.
Republic	Republic Aviation Corporation
Ryan	Ryan Aeronautical Company
Stinson	Stinson Division, Consolidated Vultee Aircraft Corporation
Vought	Chance Vought Aircraft Division of United Aircraft Corporation

Propellers

Aeroproducts Division	Aeroproducts Division, General Motors Corporation
Curtiss Propeller Division	Curtiss-Wright Corporation, Propeller Division
Hamilton Standard Propellers	Hamilton Standard Propellers Division of United Aircraft Corporation
Sensinich	Sensinich Brothers

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